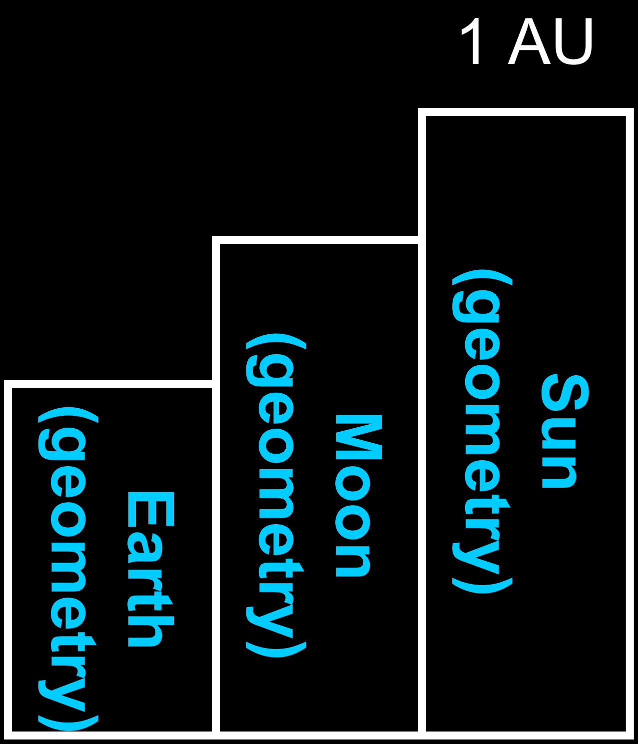
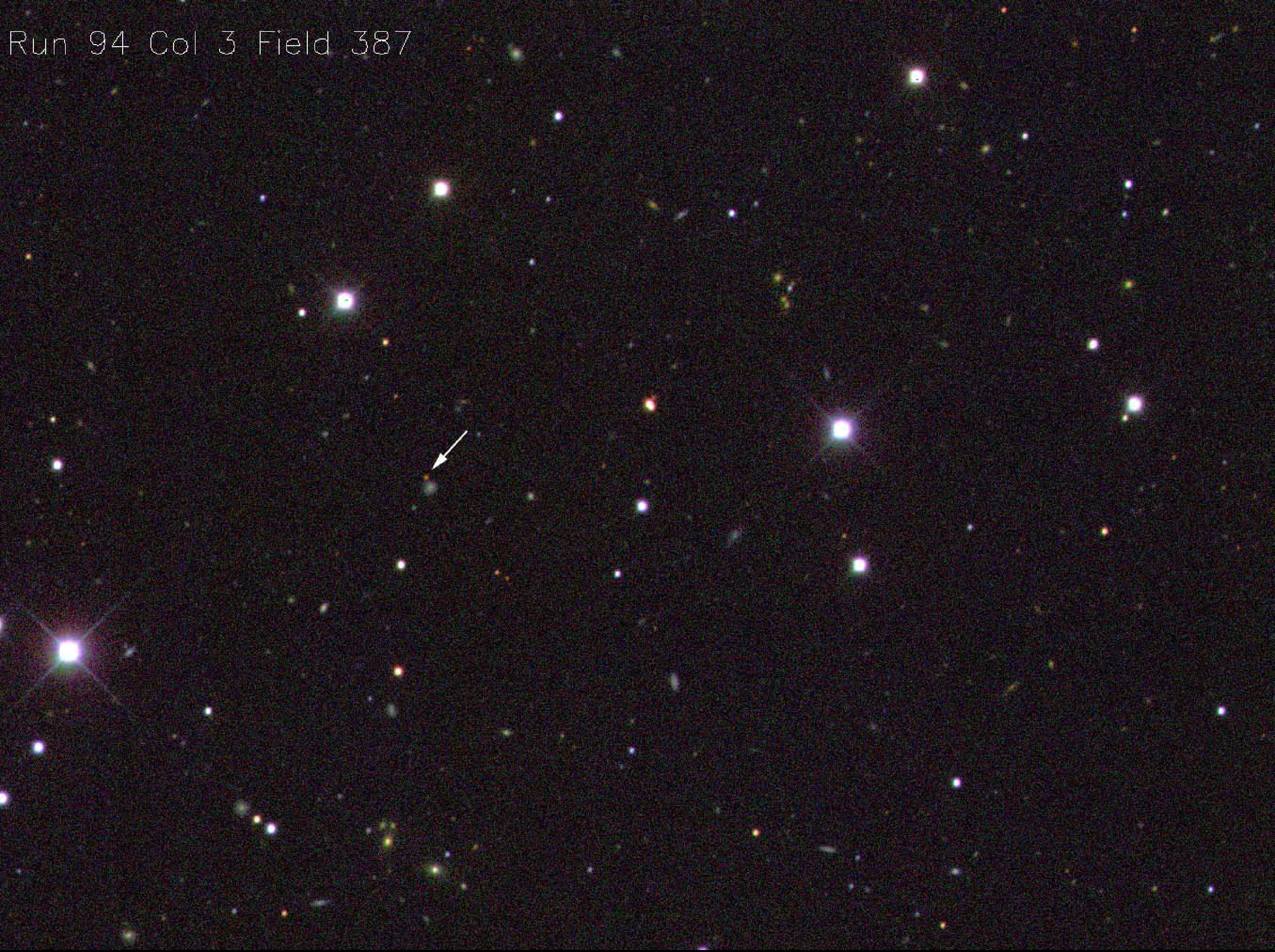
Models Lecture #6

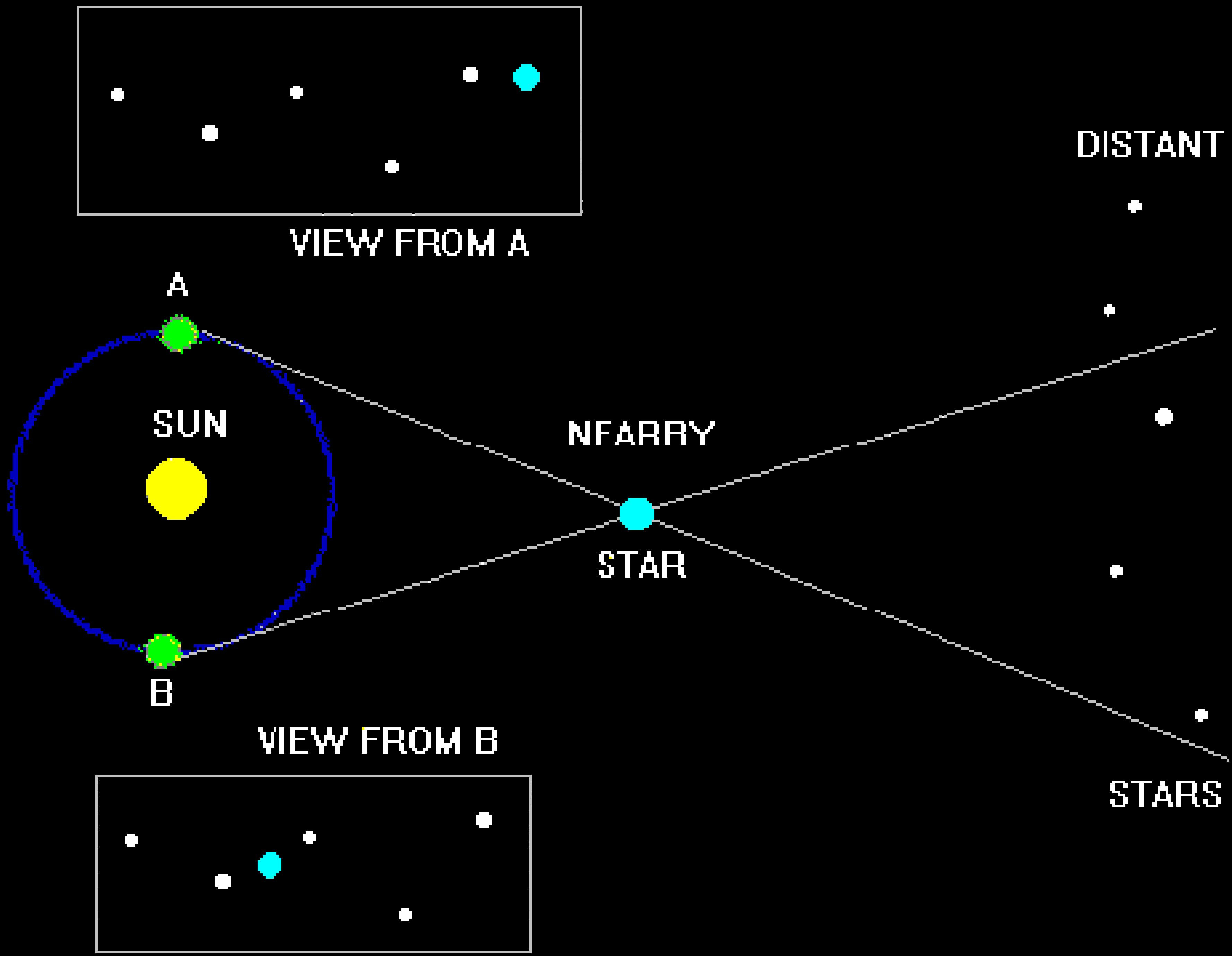
The distance ladder

The Cosmological Distance Ladder



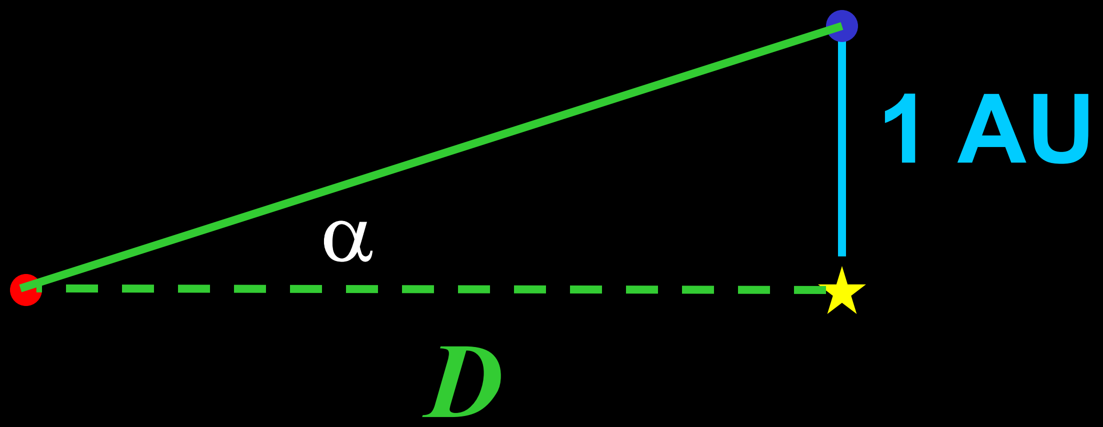

Run 94 Col 3 Field 387

They (appear to) move
They have different apparent brightness
They have different colors
They change in brightness


VIEW FROM A
A
SUN
NFARRY
STAR
B
VIEW FROM B
DISTANT
STARS

$$\frac{D}{200{,}000 \text{ AU}} = \frac{\text{seconds}}{\alpha}$$

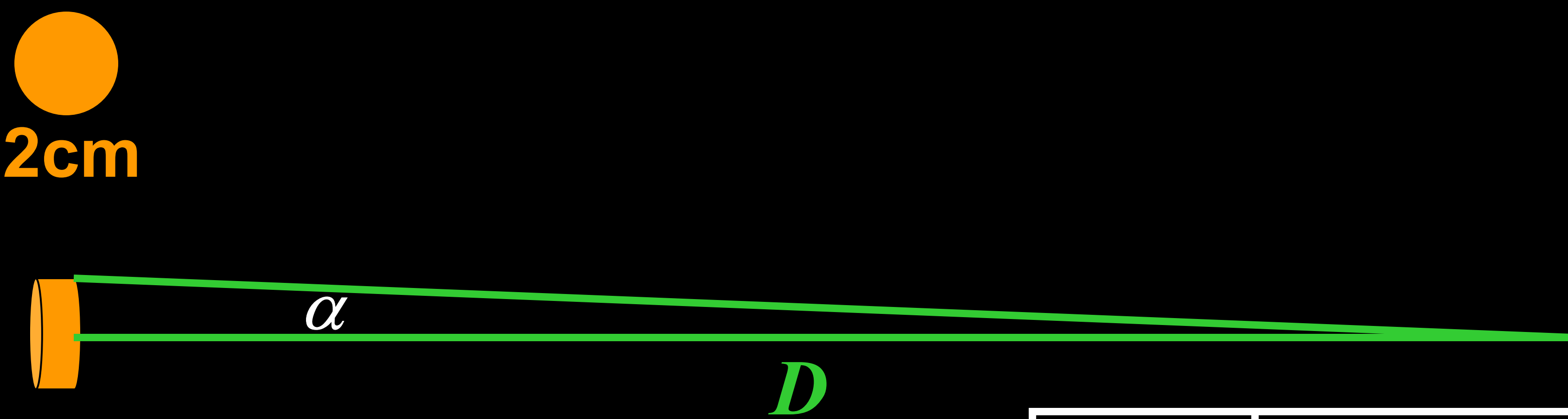
$$\frac{D}{\text{pc}} = \frac{\text{seconds}}{\alpha}$$



$$\frac{D}{\text{pc}} = \frac{\text{seconds}}{\text{parallax}}$$

star	parallax (")	distance (pc)
α Centauri	0.75	1.3
Barnard's star	0.5	2.0
Sirius	0.4	2.5
Altair	0.2	5.0

Let’s think for a second of arc



$$\alpha = \frac{2\ \text{km}}{D}\ \text{seconds}$$

α	D
4”	½ km
2”	1 km
1”	2 km
0.1”	20 km
0.01”	200 km
0”	infinity

They (appear to) move

They have different apparent brightness

They have different colors

They change in brightness

Logarithmic Eye

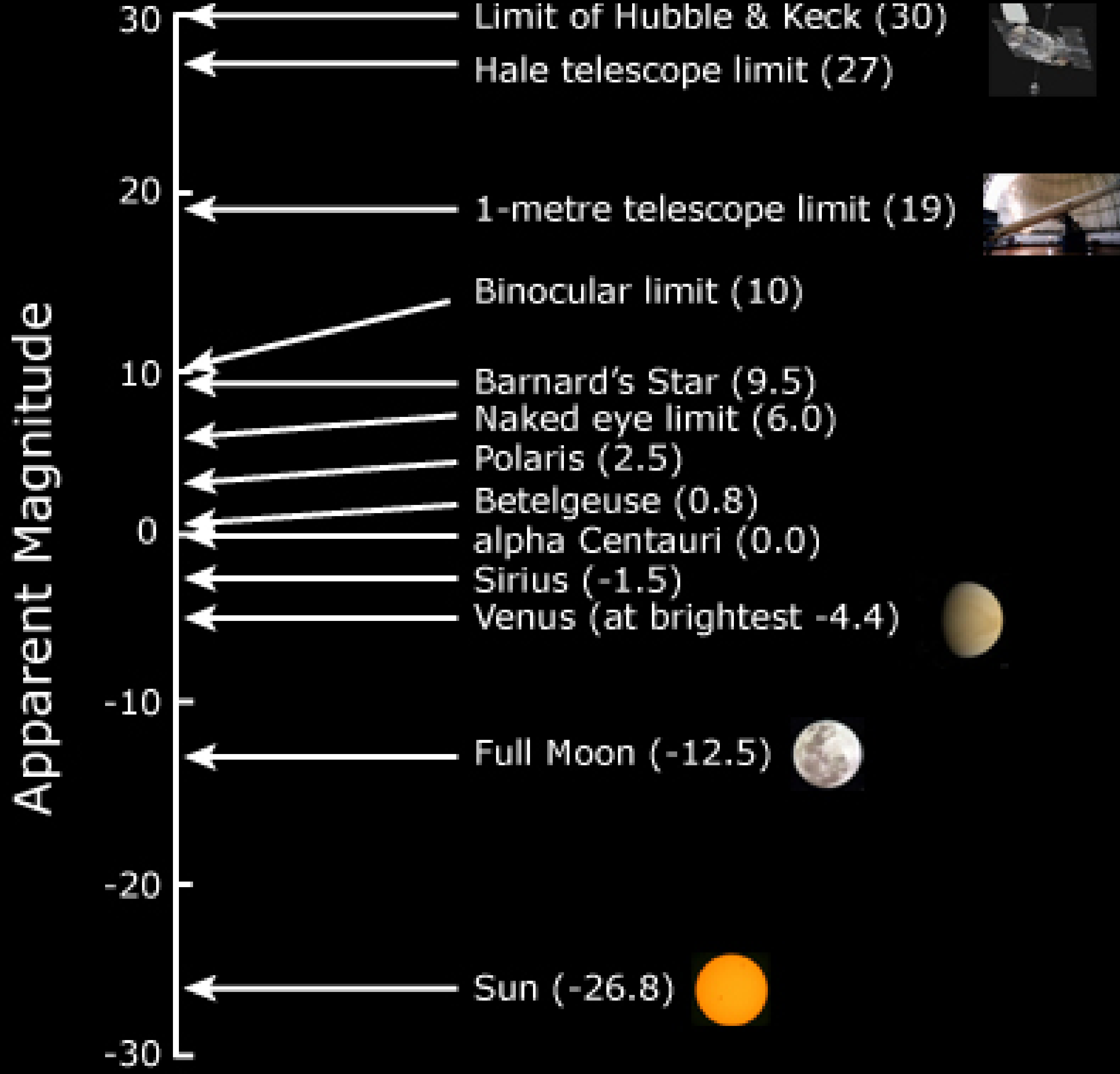
Eyes, like ears, are logarithmetic detectors.

LET THERE BE LIGHT!

Greeks classified (visible) stars into 6 classes,
or magnitudes

Brightest stars were 1st magnitude
Dimmest stars were 6th magnitude

Intensity of brightest stars = 100 X dimmest.


Apparent Magnitude
30
20
10
0
-10
-20
-30
Limit of Hubble & Keck (30)
Hale telescope limit (27)
1-metre telescope limit (19)
Binocular limit (10)
Barnard's Star (9.5)
Naked eye limit (6.0)
Polaris (2.5)
Betelgeuse (0.8)
alpha Centauri (0.0)
Sirius (-1.5)
Venus (at brightest -4.4)
Full Moon (-12.5)
Sun (-26.8)

The luminosity of nearby stars?

Measure: intensity of light, I

Intensity depends on

1. **Luminosity of source (property of source)**
2. **Distance to the source**

Inverse-square law

$$I = \frac{L}{4\pi R^2}$$

parallax → distance

$$\frac{D}{\text{pc}} = \frac{\text{seconds}}{\text{parallax}}$$

$$I = \frac{L}{4\pi R^2}$$

Measured

star	parallax (")	distance (pc)	apparent magnitude	luminosity (solar)
α Centauri	0.75	1.3	0	1.5
Barnard's star	0.5	2.0	9.5	0.0005
Sirius	0.4	2.5	-1.5	25
Altair	0.2	5.0	0.8	10
Canopus	0.003	330	- 0.7	200,000
Arcturus	0.1	10	0	90
Betelgeuse	0.01	100	0.5	14,000

Our Sun ain't the brightest bulb in the box!

$$\text{Intensity} = \frac{\text{Luminosity}}{4\pi R^2}$$

$$L_{SIRIUS} = 25 \times L_{SUN}$$

For stars we know distance to via parallax:

Measure Distance (R)
Measure Intensity
$\longrightarrow$ Know Luminosity

They (appear to) move

They have different apparent brightness

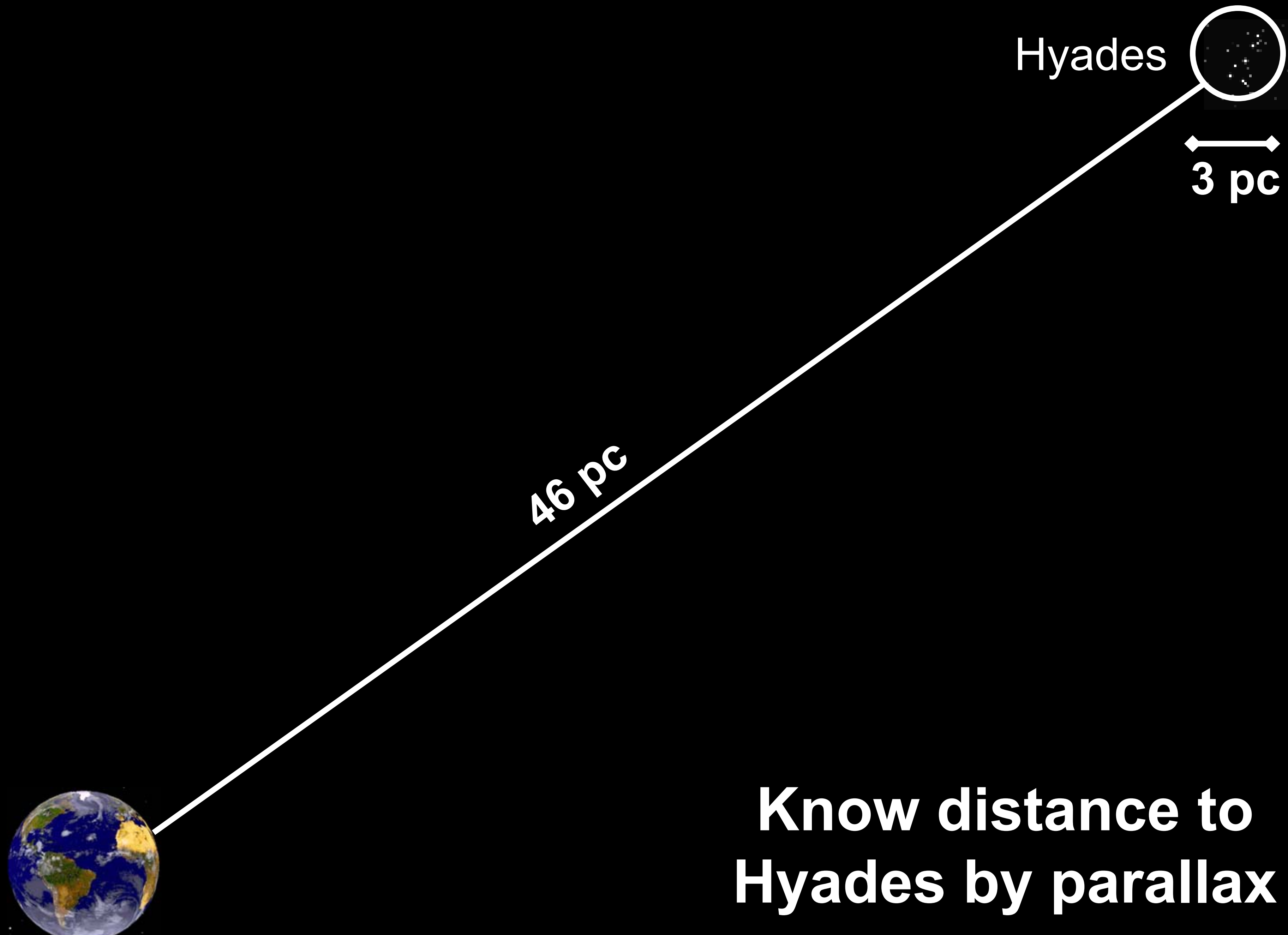
They have different colors

They change in brightness

COLORS OF THE RAINBOW:

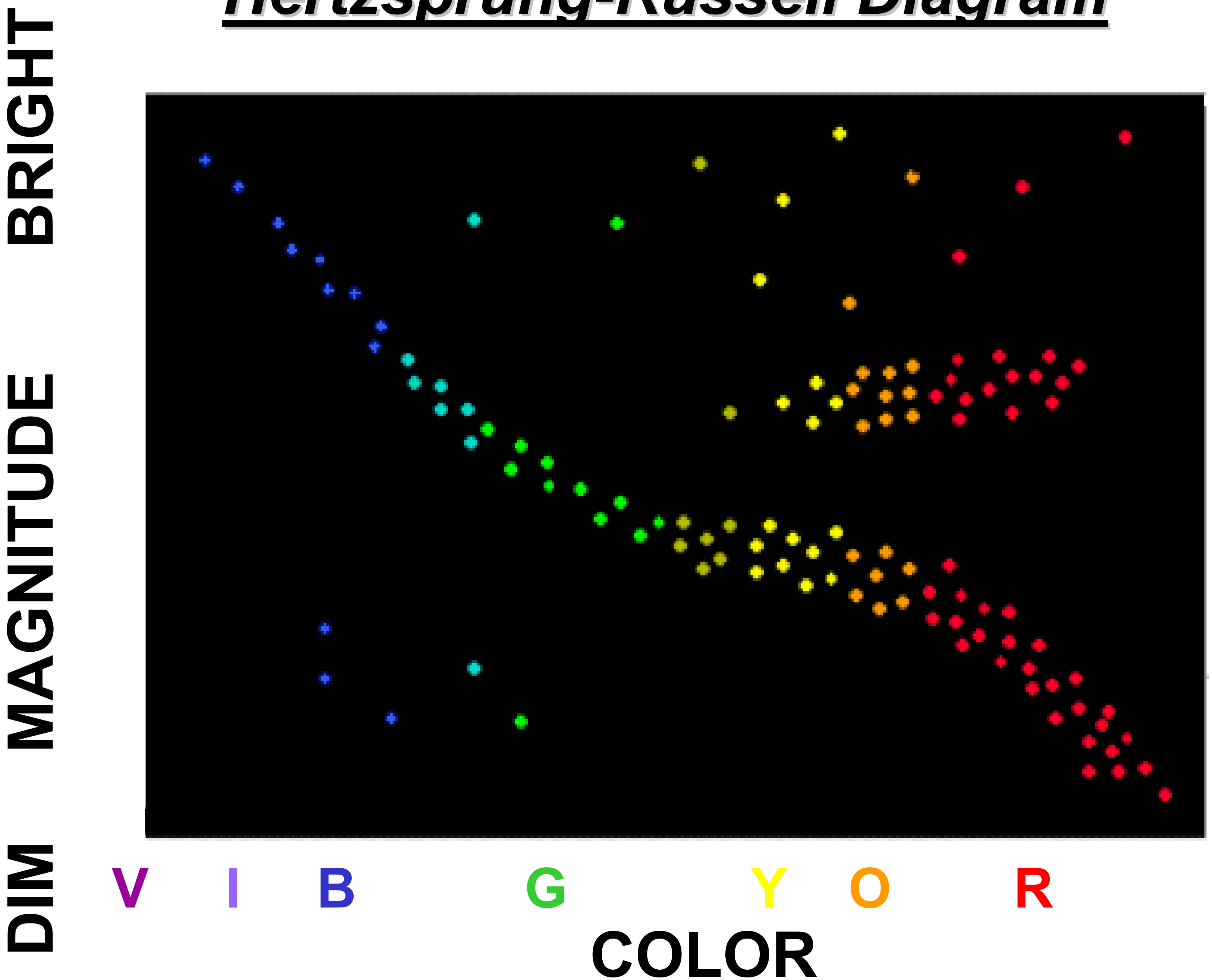
R O Y G B I V


M 45 (Pléiades)
Hyades
© Denis Bergeron 1980

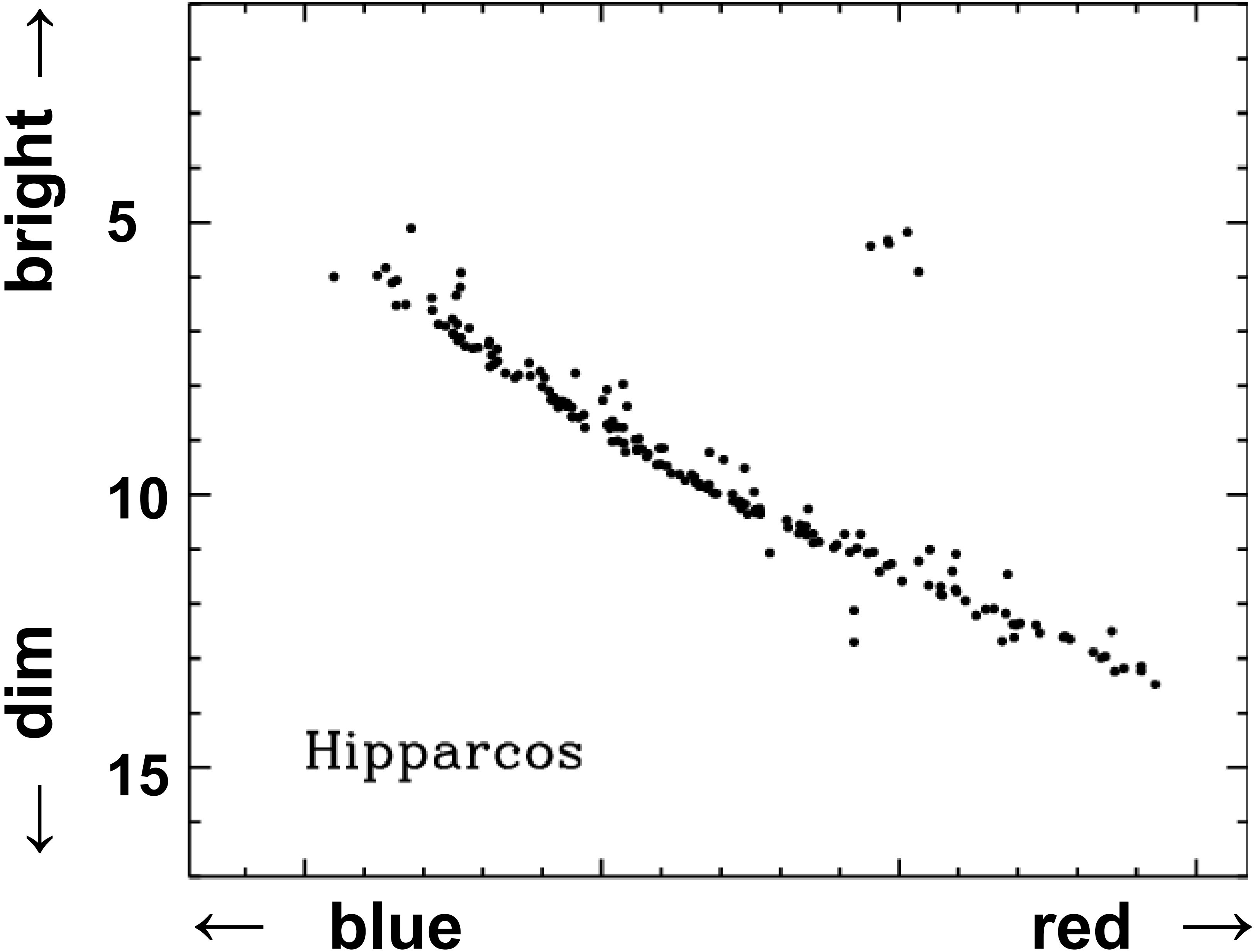


Know distance to Hyades by parallax

Hertzsprung-Russell Diagram

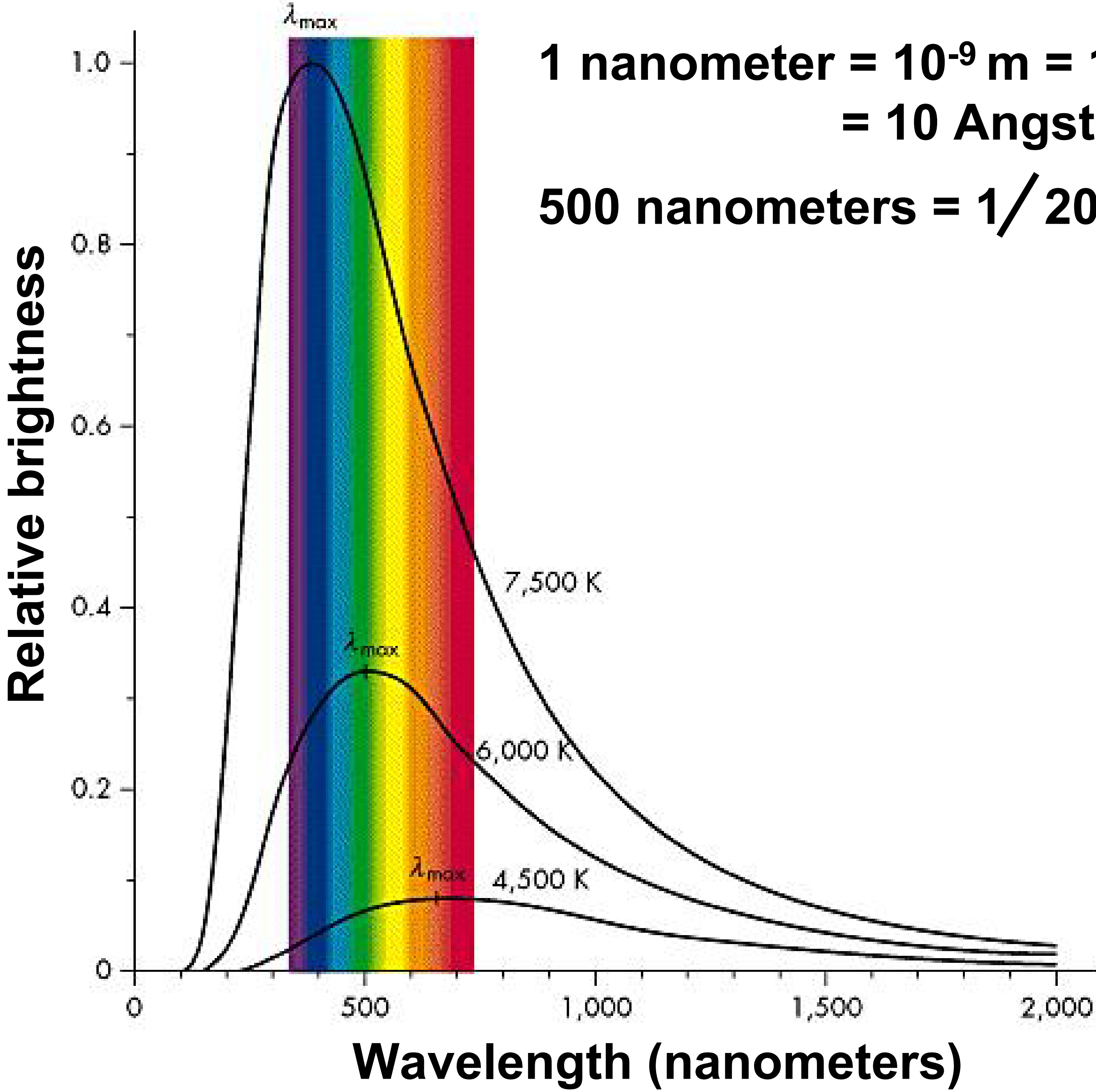


Hyades HR diagram

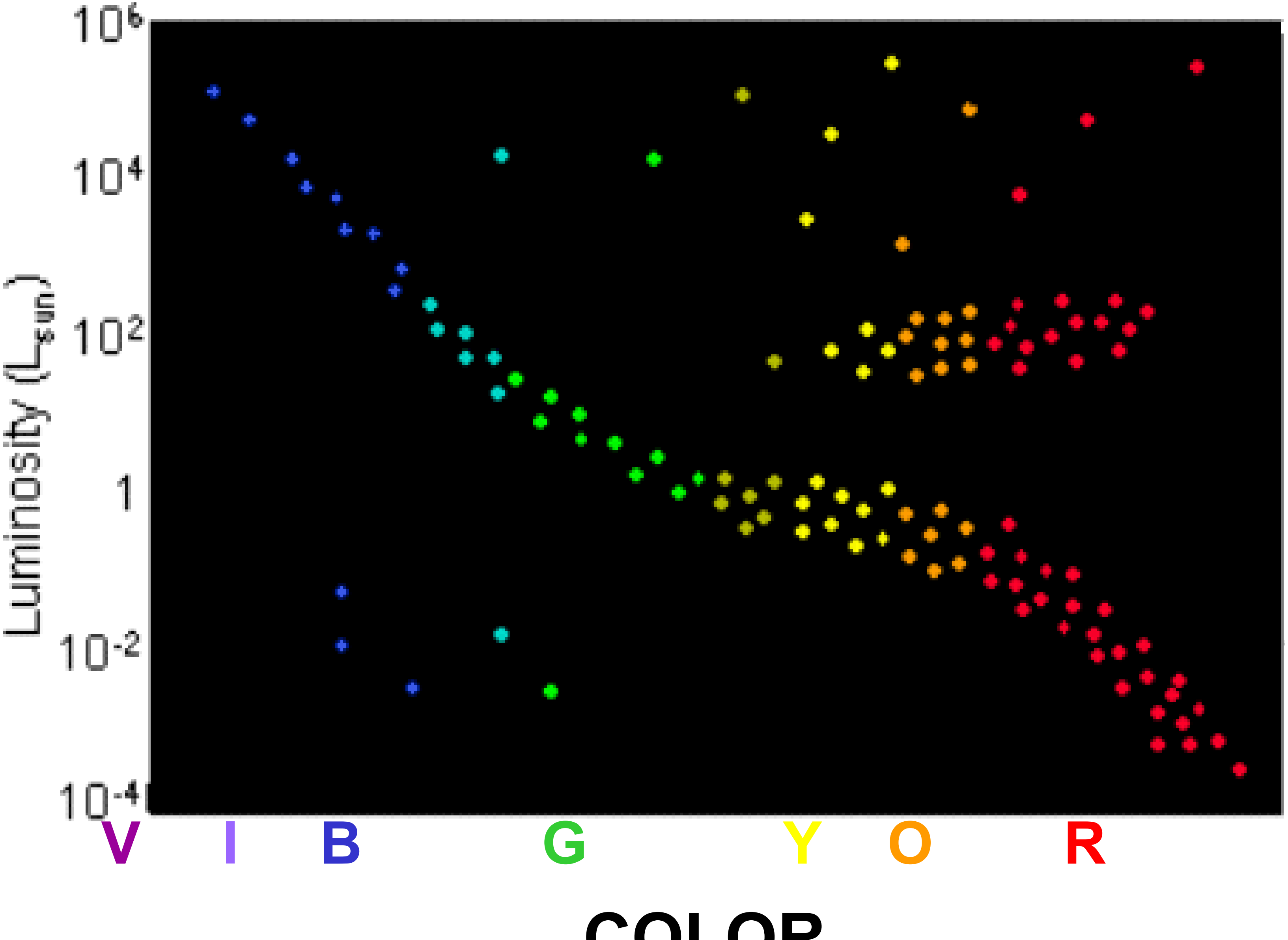


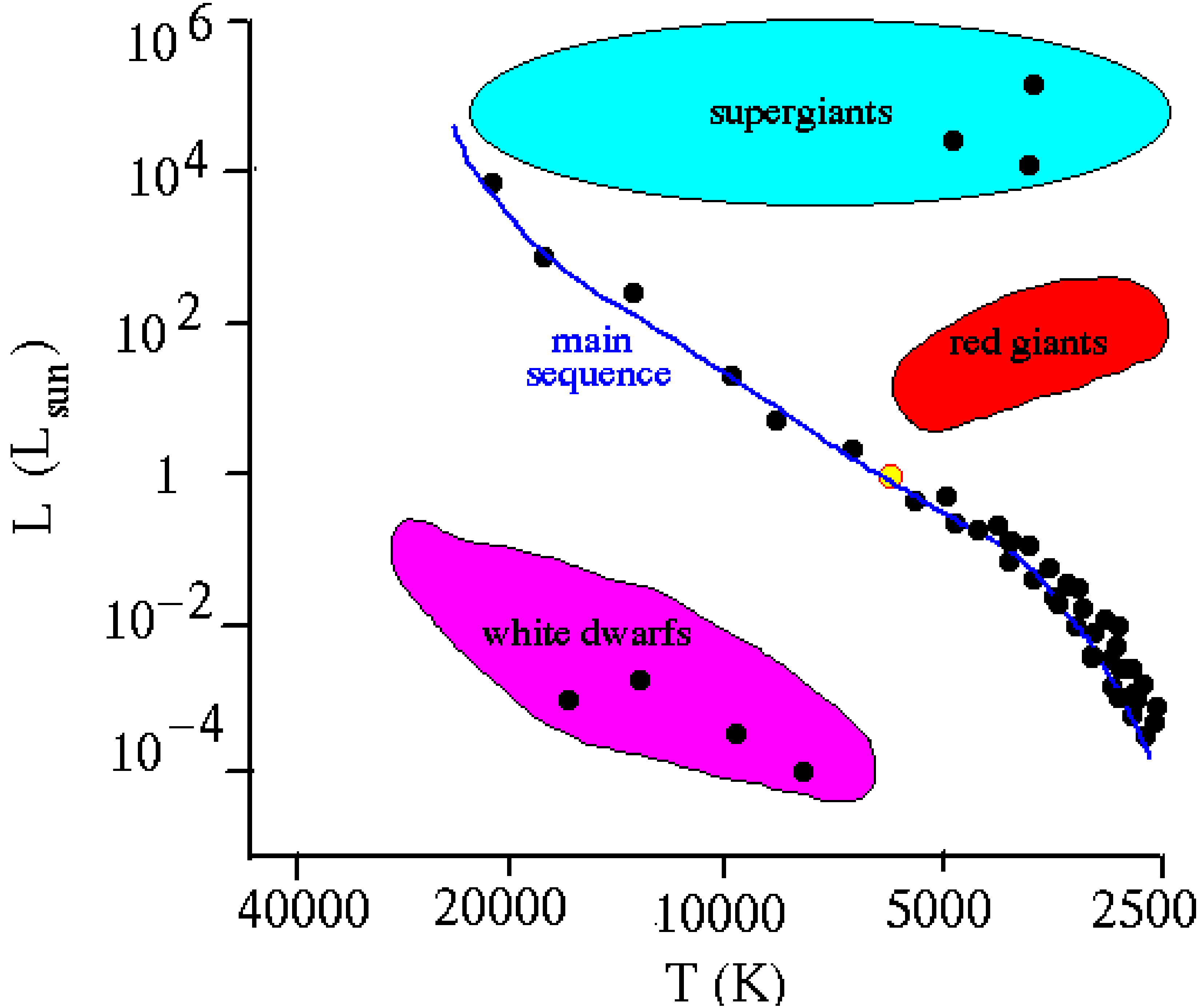
1 nanometer = 10^{-9} m = 10^{-7} cm
= 10 Angstroms

500 nanometers = 1/20,000 cm

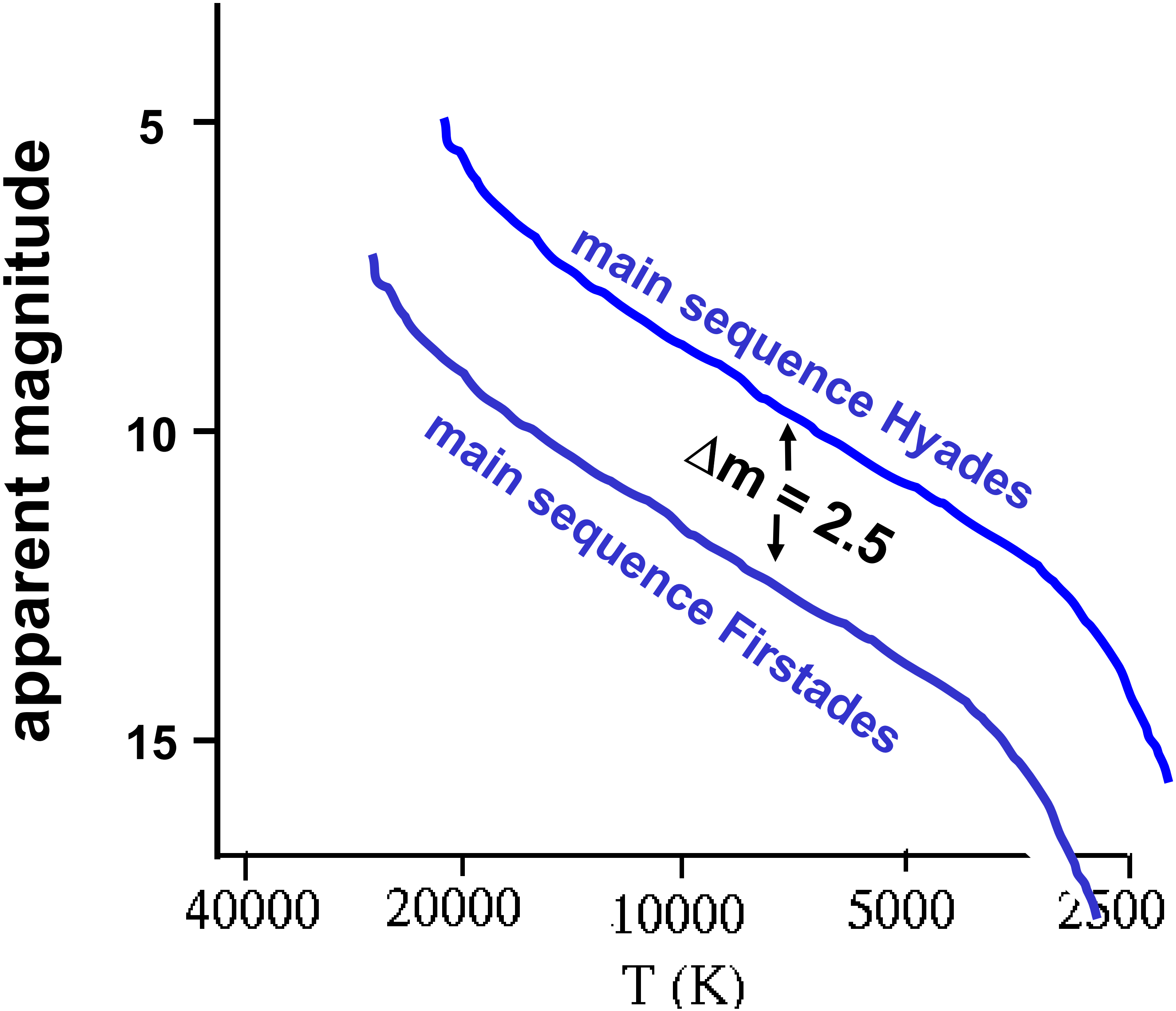


Schematic Hertzsprung-Russell Diagram





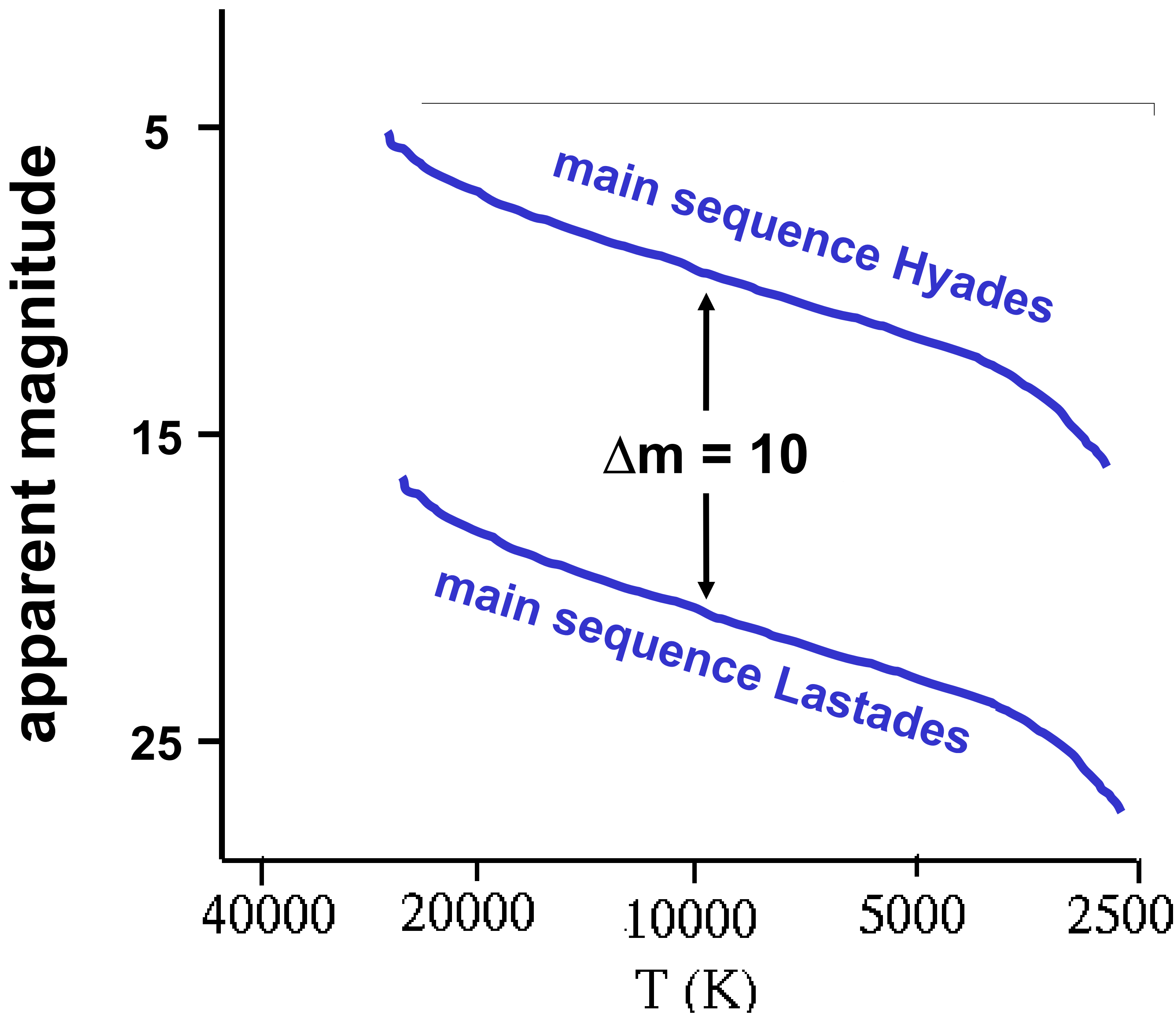
supergiants
red giants
main sequence
white dwarfs
10^6
10^4
10^2
1
10^{-2}
10^{-4}
L (L_{sun})
40000
20000
10000
5000
2500
T (K)



apparent magnitude
5
10
15
main sequence Hyades
main sequence Firstades
Δm = 2.5
40000
20000
10000
5000
2500
T (K)

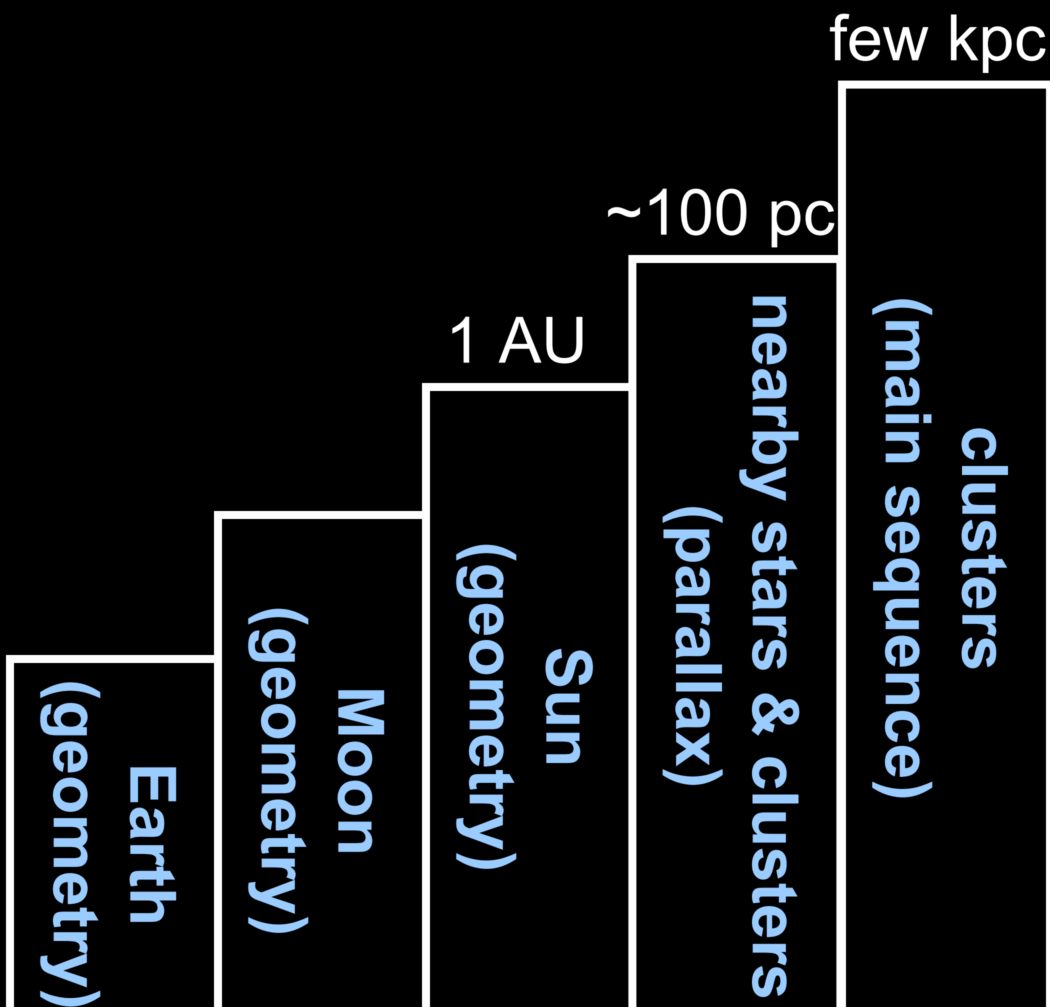
Distances to other clusters

- Construct H-R diagram for cluster
- Measure Δm compared to HR diagram for Hyades
- Compute distance in terms of distance to Hyades
- How far can you go?
- Say most distant open observable cluster is Lastades



apparent magnitude
5
15
25
main sequence Hyades
Δm = 10
main sequence Lastades
40000
20000
10000
5000
2500
T (K)

The Cosmological Distance Ladder

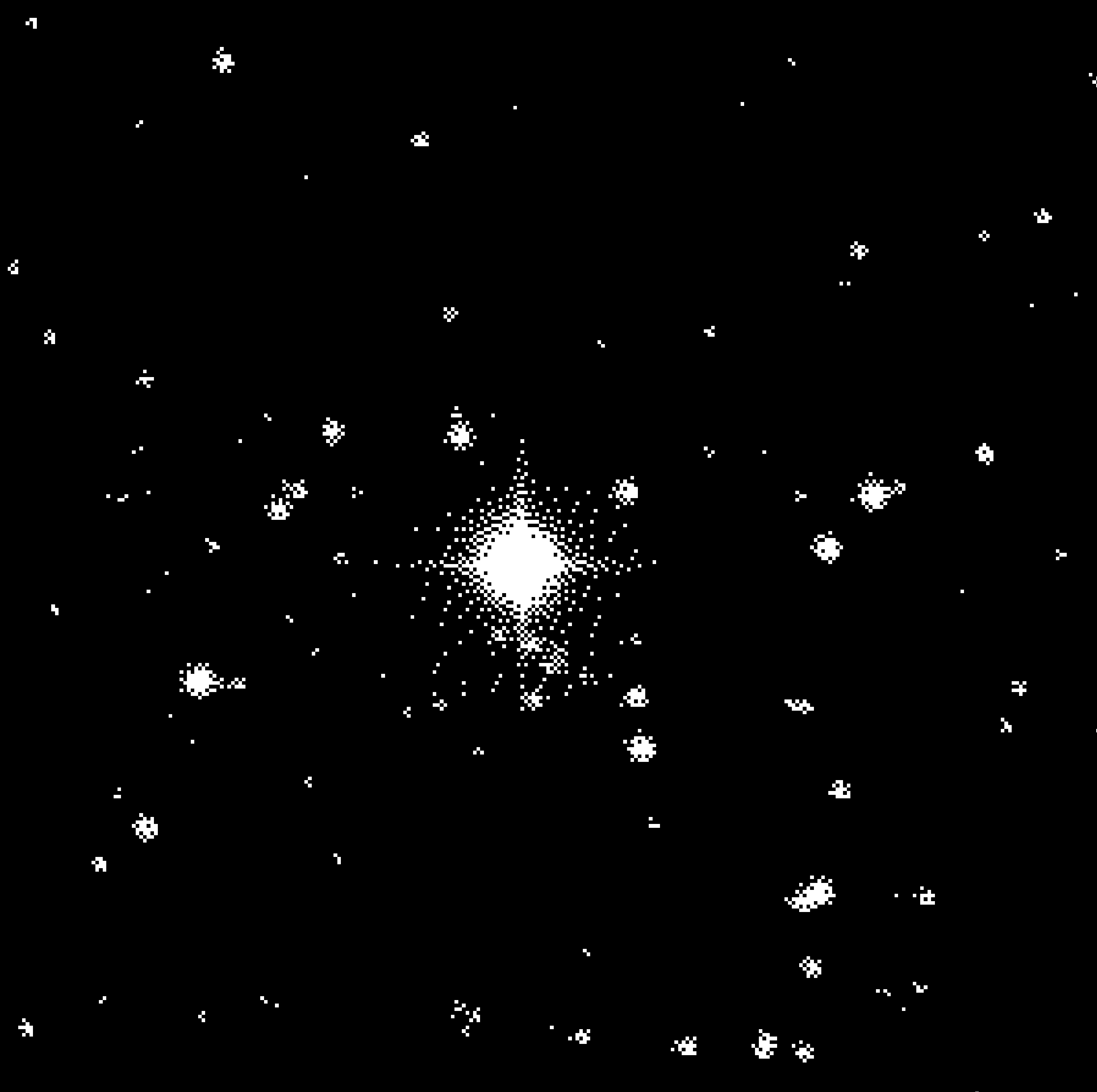


- Main sequence stars are not extremely bright… we need brighter “standard candle”

$$\text{Intensity} = \frac{\text{Luminosity}}{4\pi R^2}$$

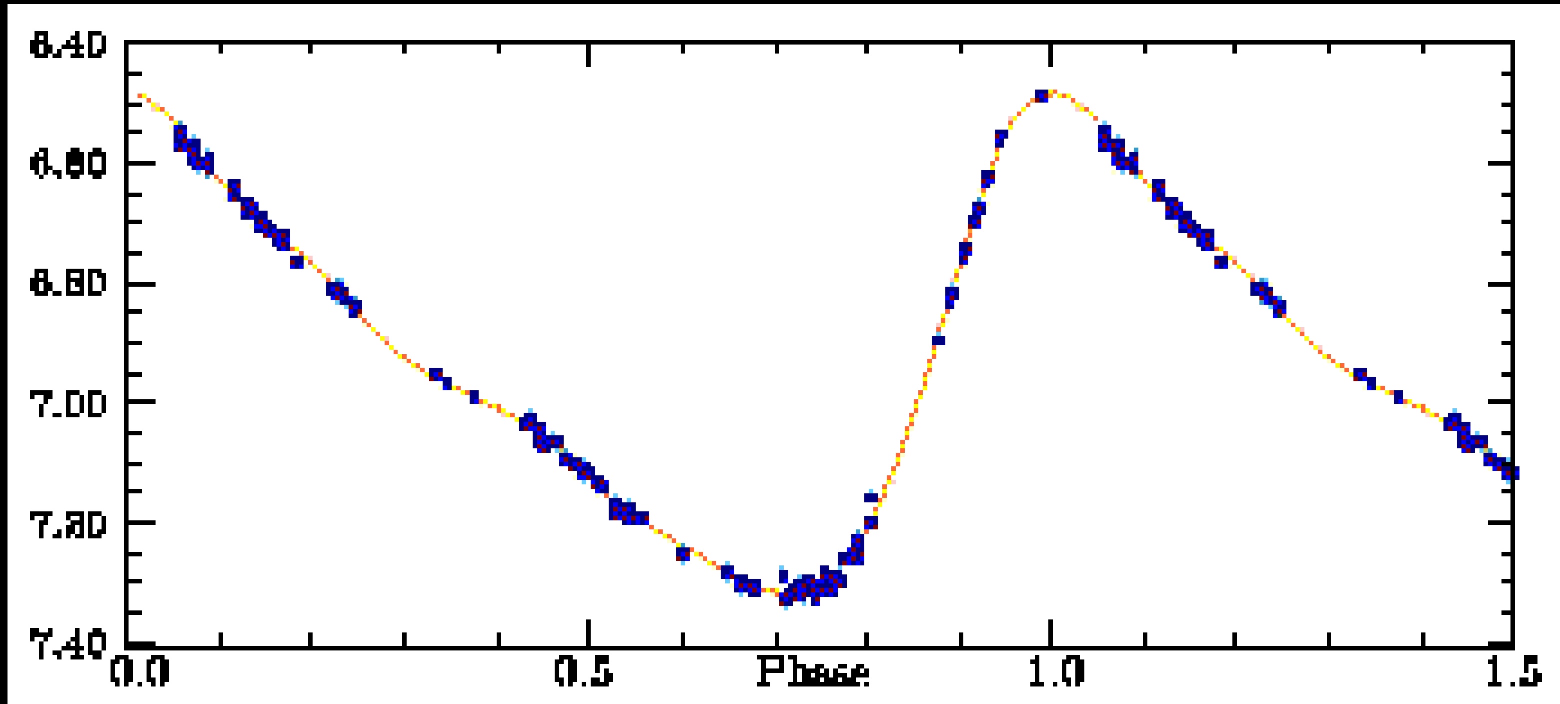
They (appear to) move
They have different apparent brightness
They have different colors
They change in brightness

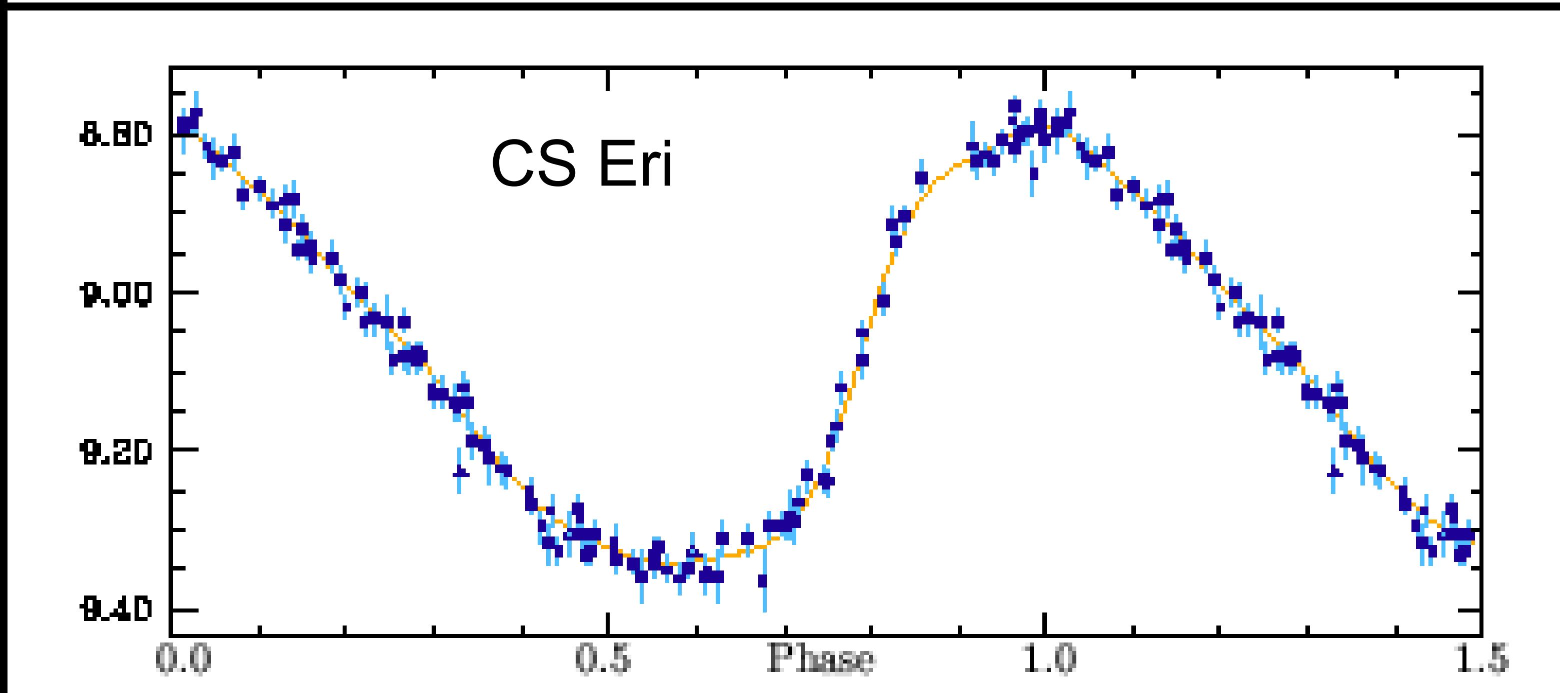
RR Lyrae Stars



RR Lyrae Stars

- Class named after a particular star: RR Lyrae
- Compared to the sun
  - half the mass
  - older than sun
  - hotter
  - expended hydrogen … burning helium to carbon
  - pulsates
- Changes brightness with regular period of days
- Luminosity determined by size & temperature
  - for same temperature: larger $\rightarrow$ more luminous
  - for same size: hotter $\rightarrow$ more luminous
- Shrink $\rightarrow$ compressional heating $\rightarrow$ more luminous


6.40
6.60
6.80
7.00
7.20
7.40
0.0
0.5
Phase
1.0
1.5


CS Eri
8.80
9.00
9.20
9.40
0.0
0.5
Phase
1.0
1.5

- Main sequence stars are not extremely bright… we need brighter "standard candle"

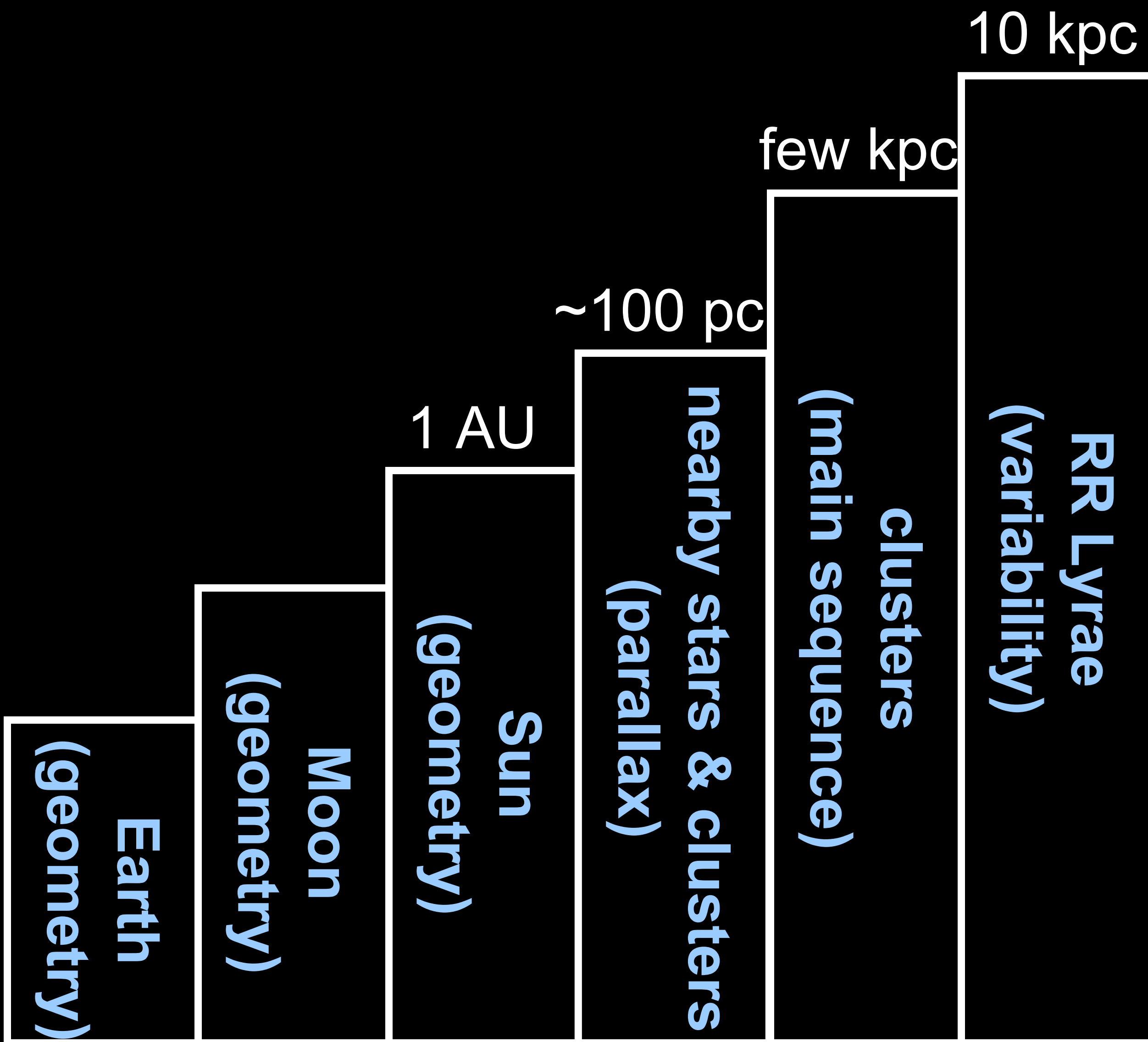
$$\text{Intensity} = \frac{\text{Luminosity}}{4\pi R^2}$$

- RR Lyrae stars found in distant clusters we know the distance to via H-R fitting.

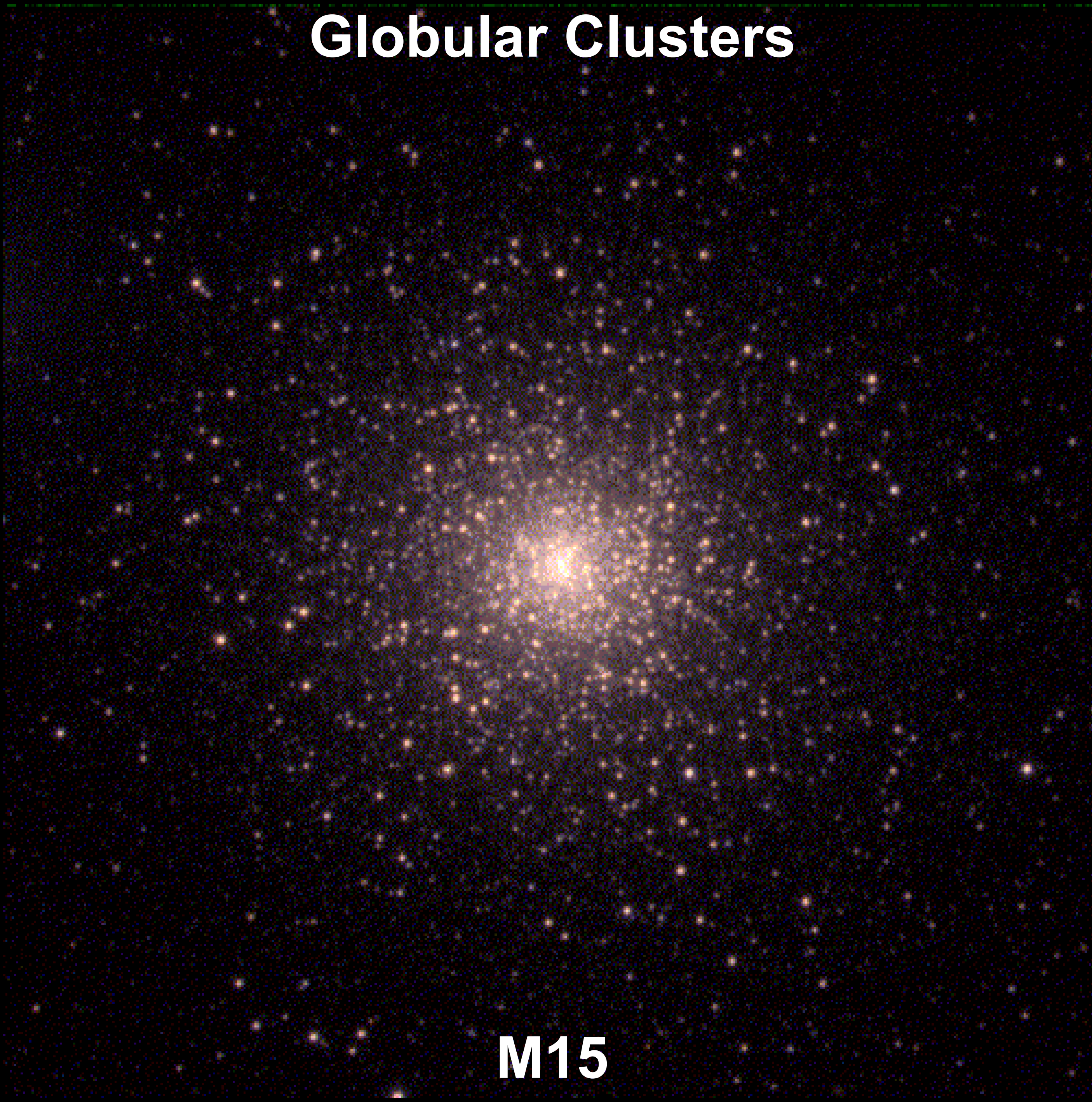
- RR Lyrae stars are identified because their light output changes regularly on a time scale of half to one day.

- They are brighter than the sun by about a factor of 100 and are <u>standard candles</u>. Can see farther away and use as standard candle.

The Cosmological Distance Ladder



Globular Clusters



M15

• Need brighter "standard candle"

$$\text{Intensity} = \frac{\text{Luminosity}}{4\pi R^2}$$

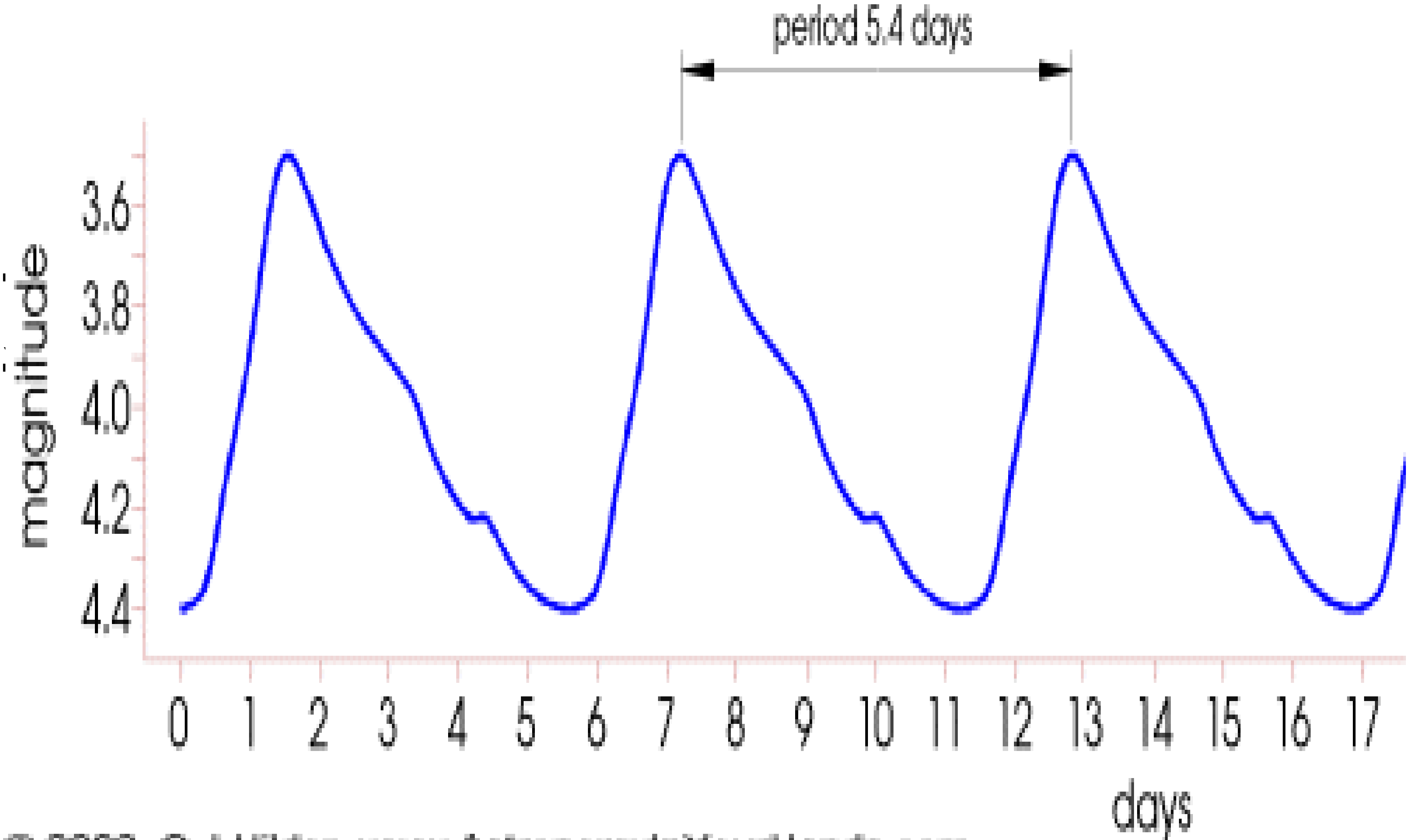
• Other variable stars are brighter: Cepheid Stars (Polaris is a Cepheid)

• Cepheid stars are identified because their light output changes regularly on a time scale of weeks to months. They are very rare.

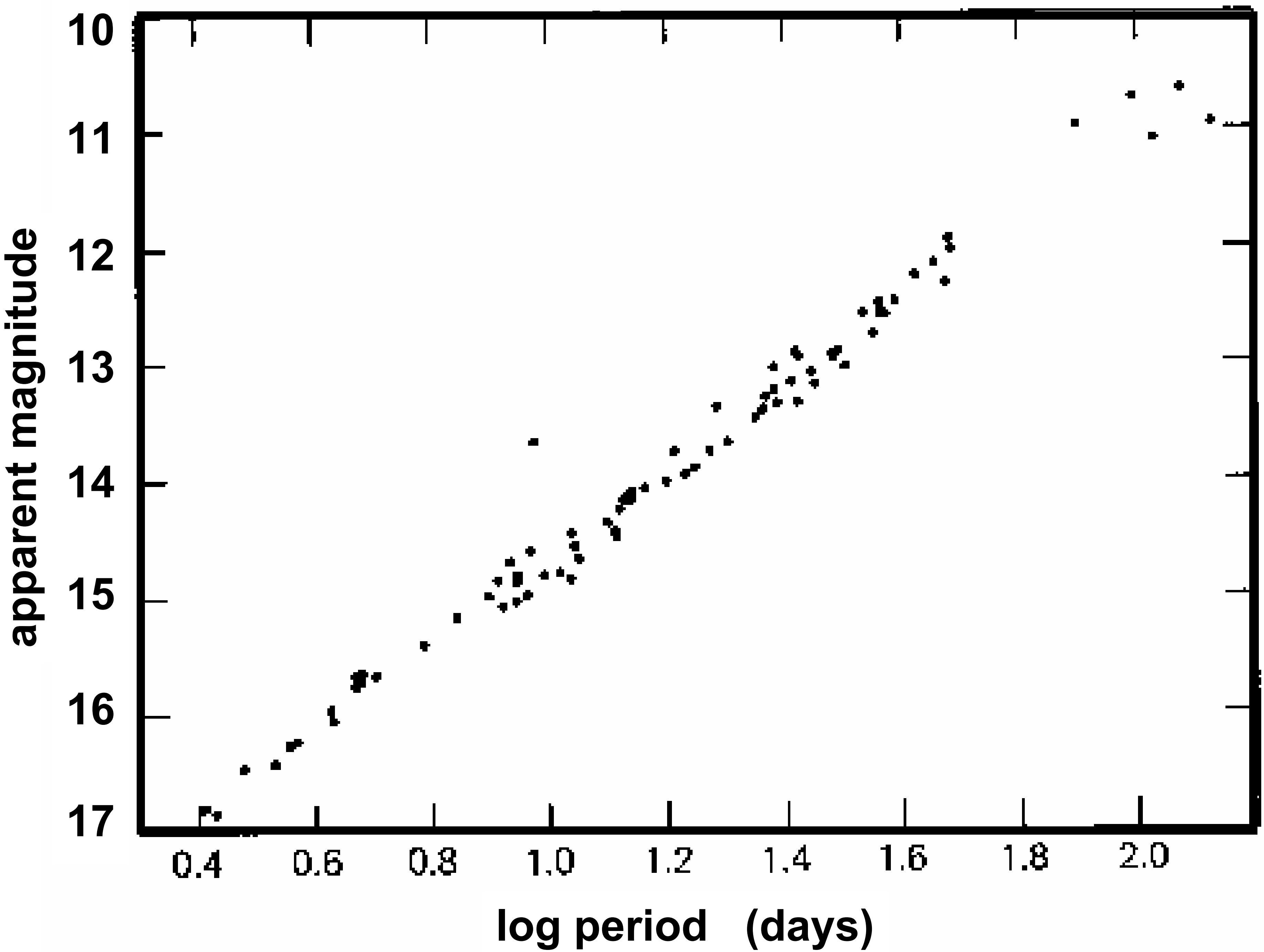
• They are brighter than the sun by about a factor of 10,000 but are <u>not</u> standard candles.

Cepheid Variable Stars

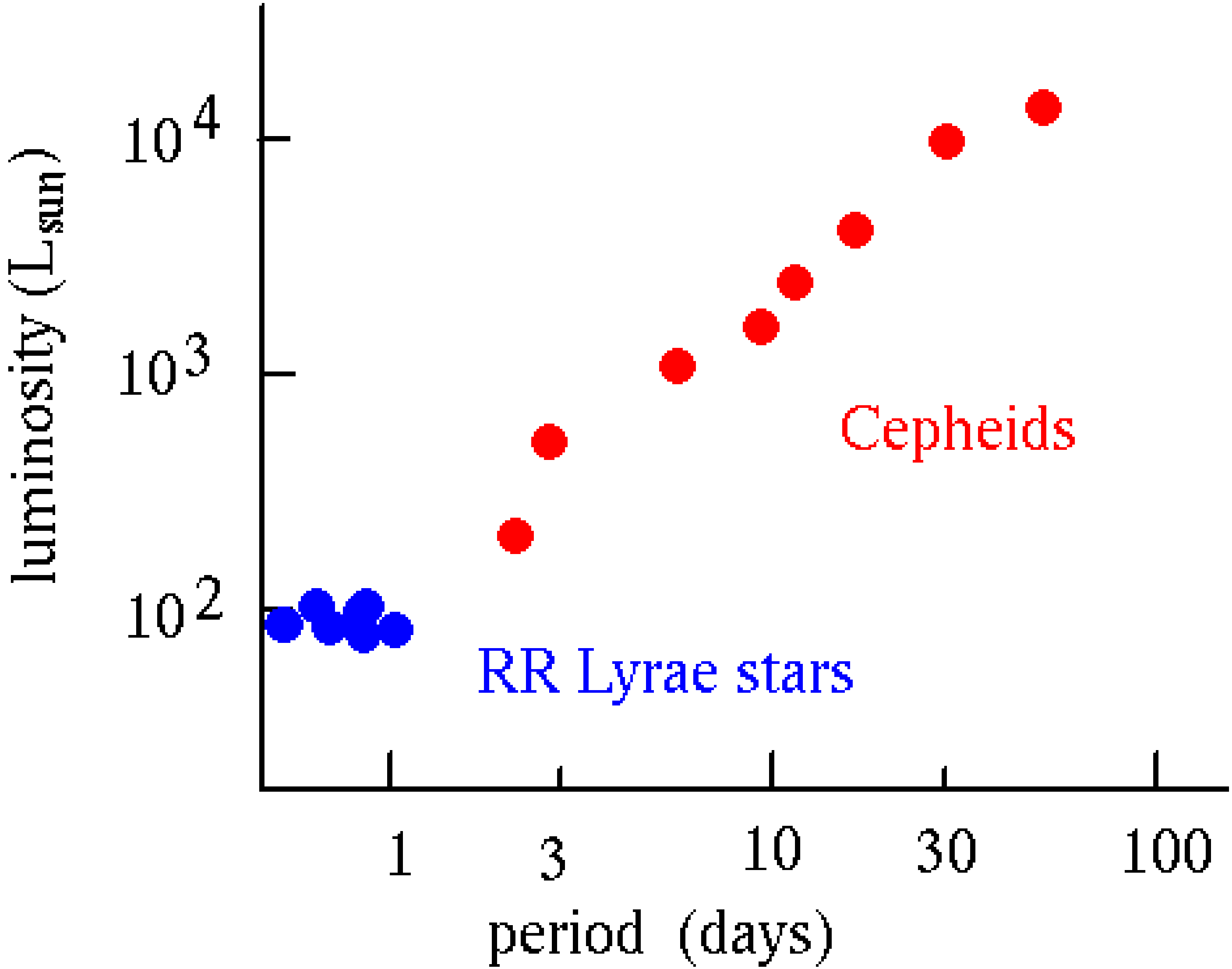
Henrietta Leavitt
1868 - 1921



Light curve of Delta Cephei



10
11
12
13
14
15
16
17
apparent magnitude
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
log period (days)



luminosity (L_{sun})
10^4
10^3
10^2
Cepheids
RR Lyrae stars
1
3
10
30
100
period (days)

Cepheids as distance indicators

For cepheids of known distance

- Measure apparent magnitude of the cepheids

$$I = \frac{L}{4\pi R^2} \rightarrow \text{know } L$$

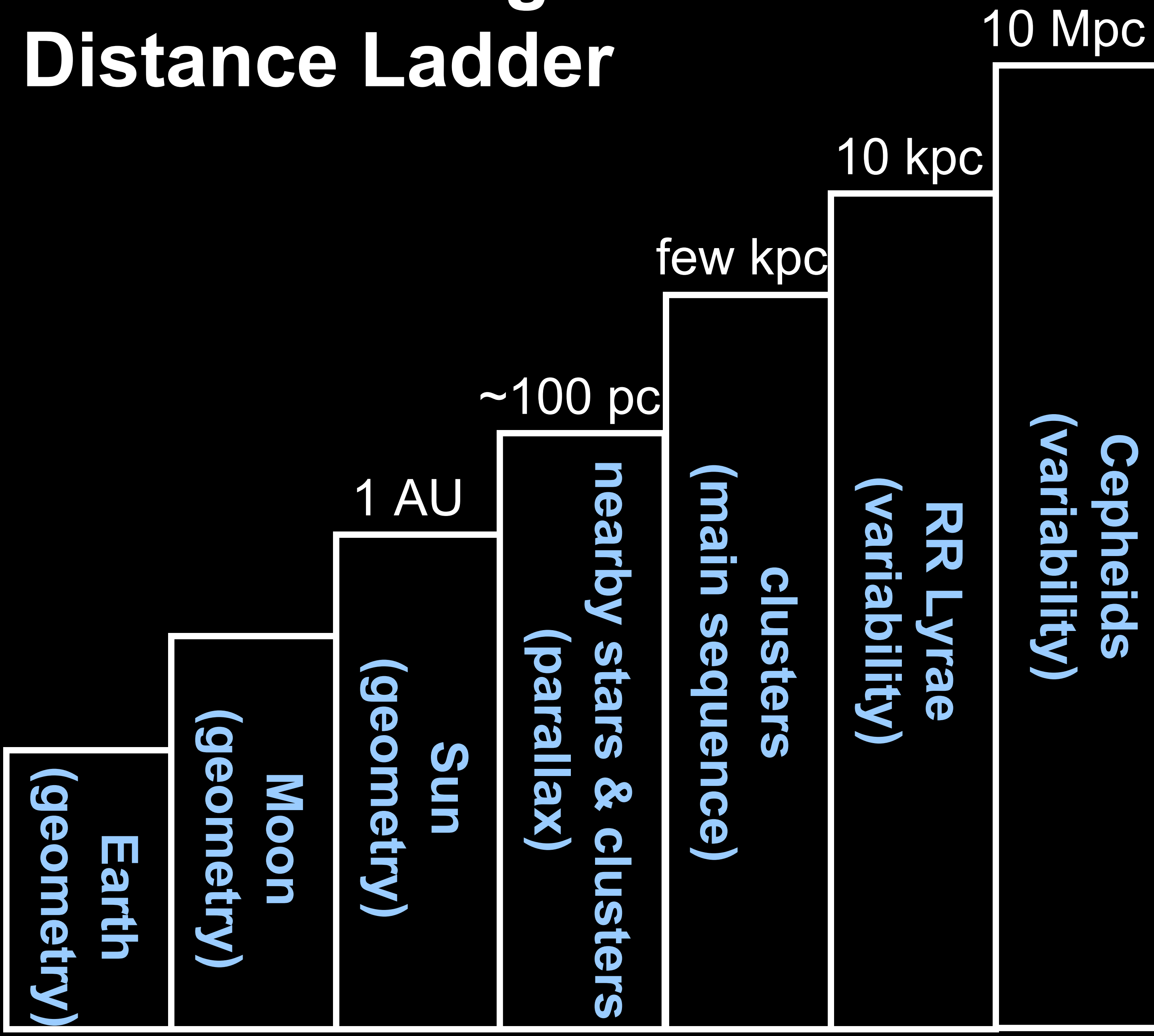
- Measure period of the cepheids
- Calibrate (if know period know L)

For cepheids of unknown distance

- Measure period….know L
- Measure apparent magnitude

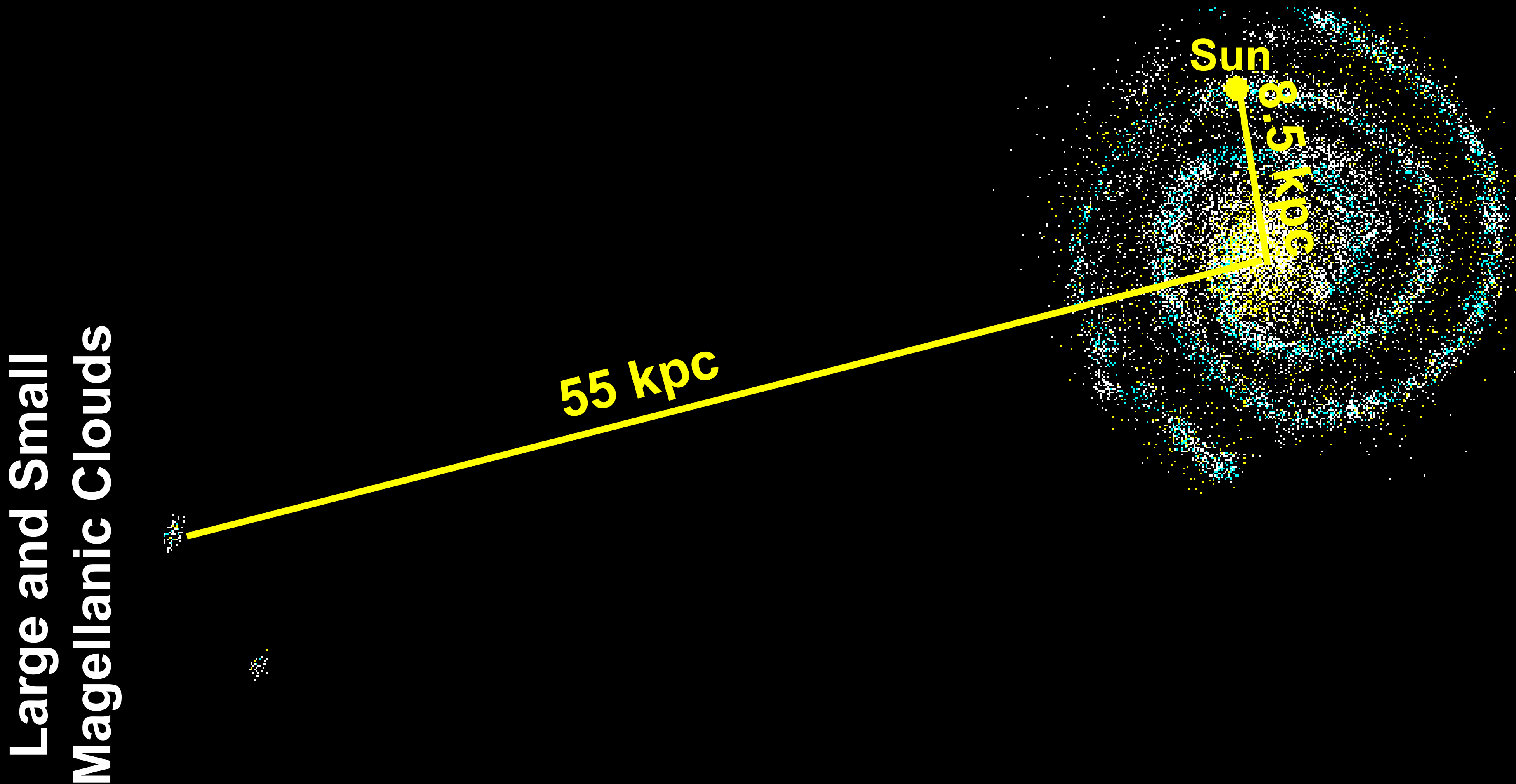
$$I = \frac{L}{4\pi R^2} \rightarrow \text{know } R$$

The Cosmological Distance Ladder

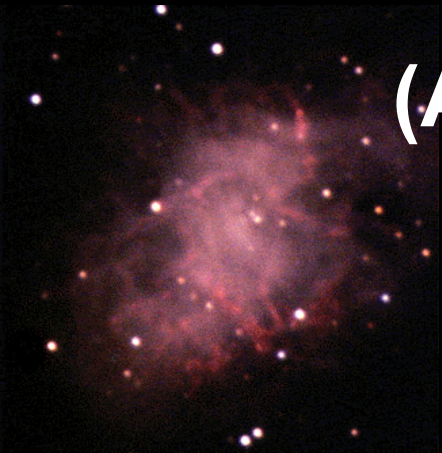
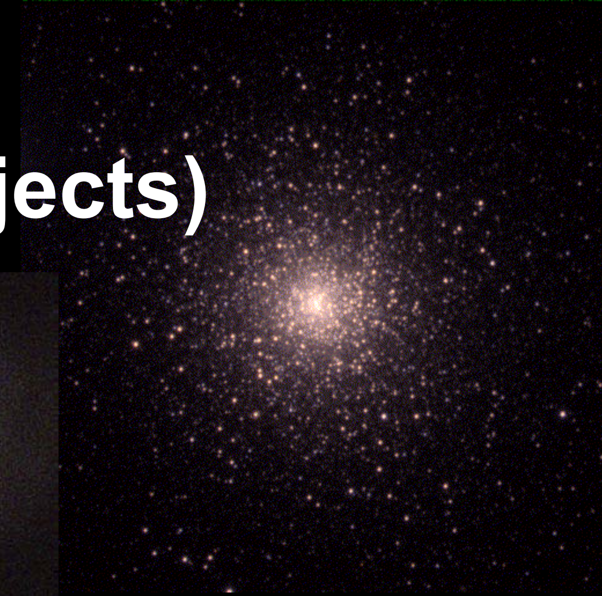


Large Magellanic Cloud   100 million stars   55 kpc distant

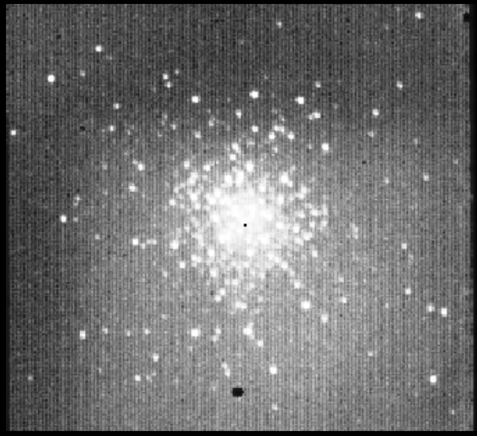
Milky Way Galaxy



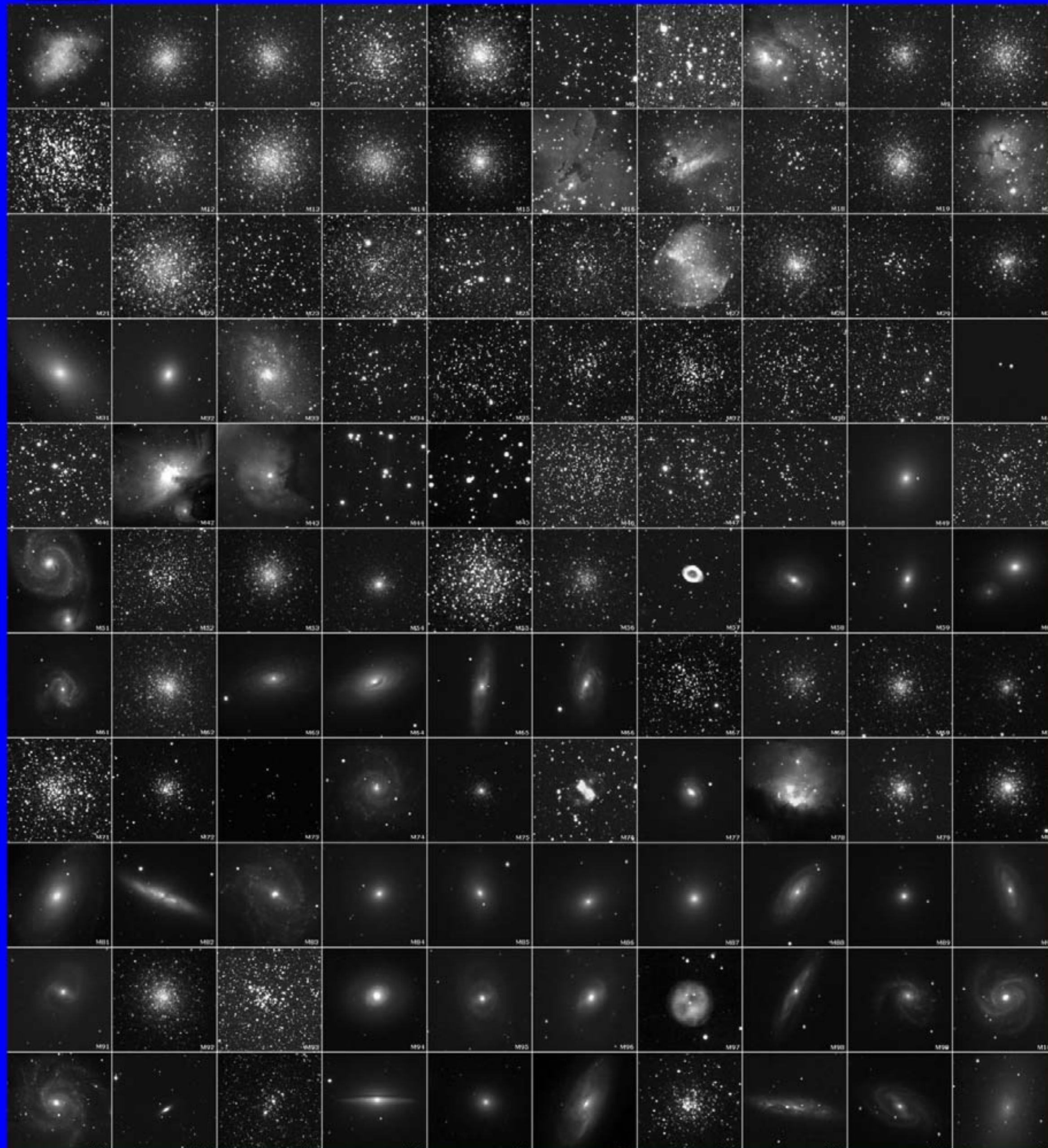
Clouds in the Sky
(A Mess of Messier Objects)

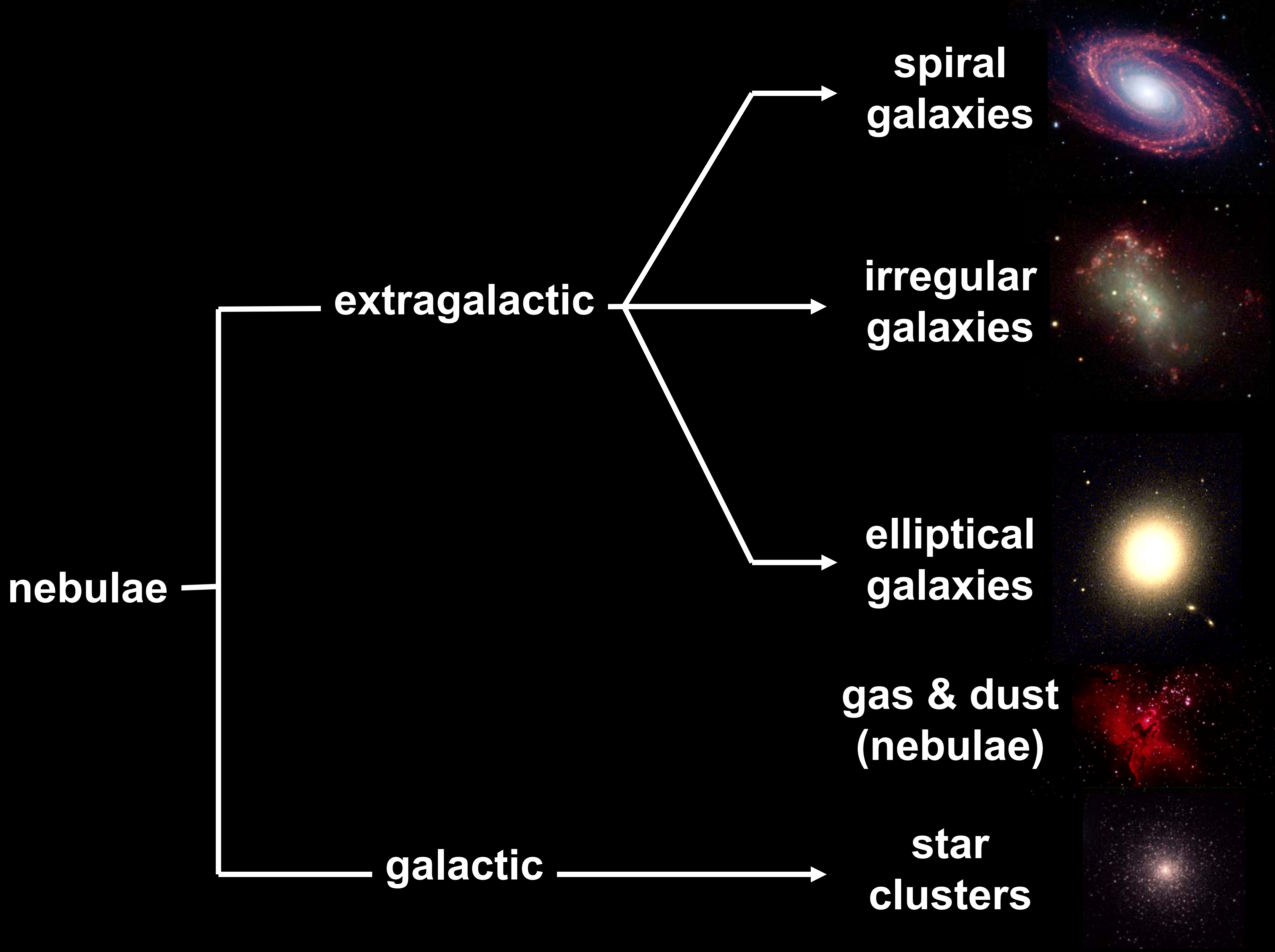






MESSIER CATALOGUE




nebulae
extragalactic
galactic
spiral galaxies
irregular galaxies
elliptical galaxies
gas & dust (nebulae)
star clusters

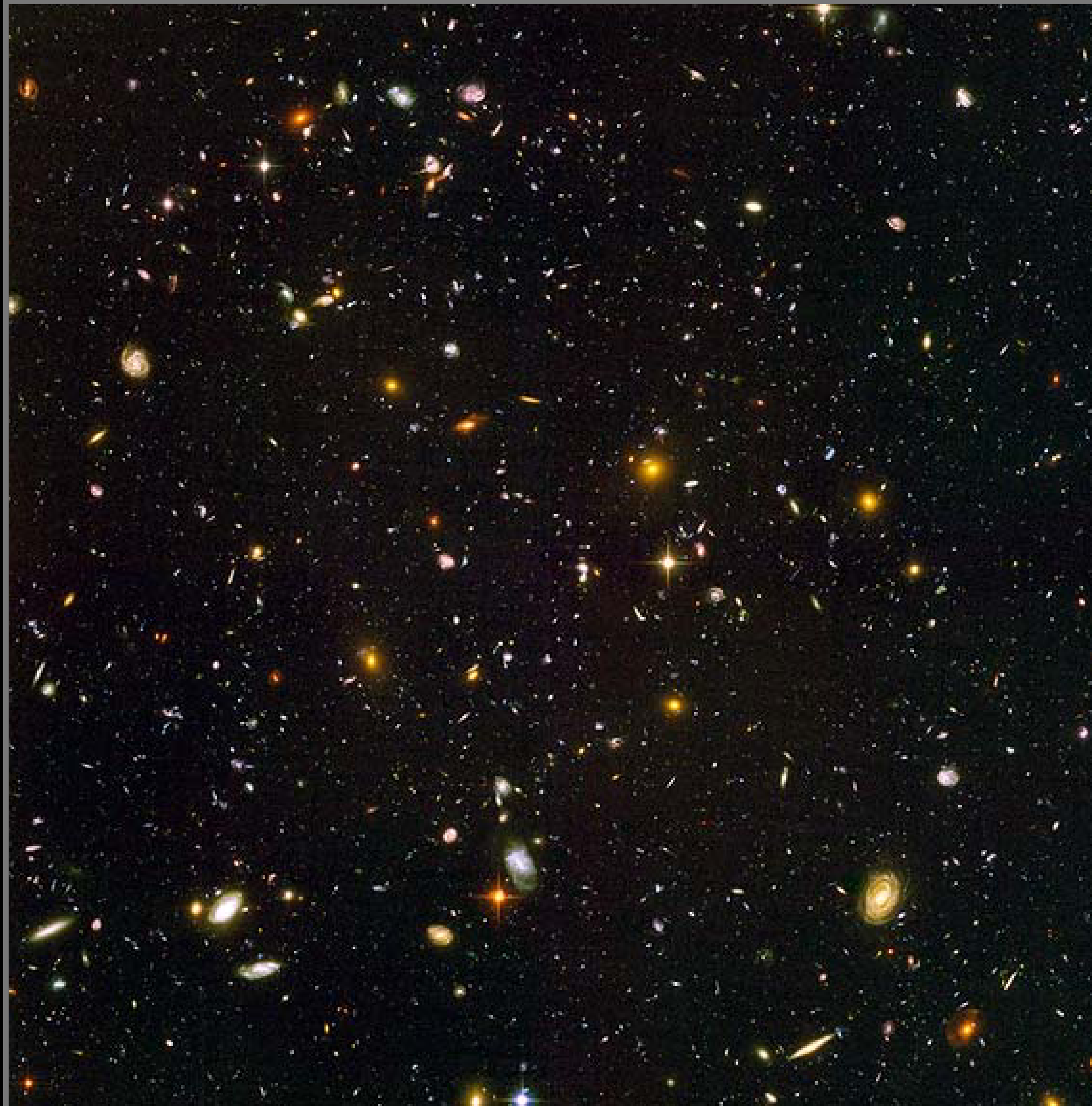
Eagle Nebula

The composition of the universe

Hubble Ultradeep Field

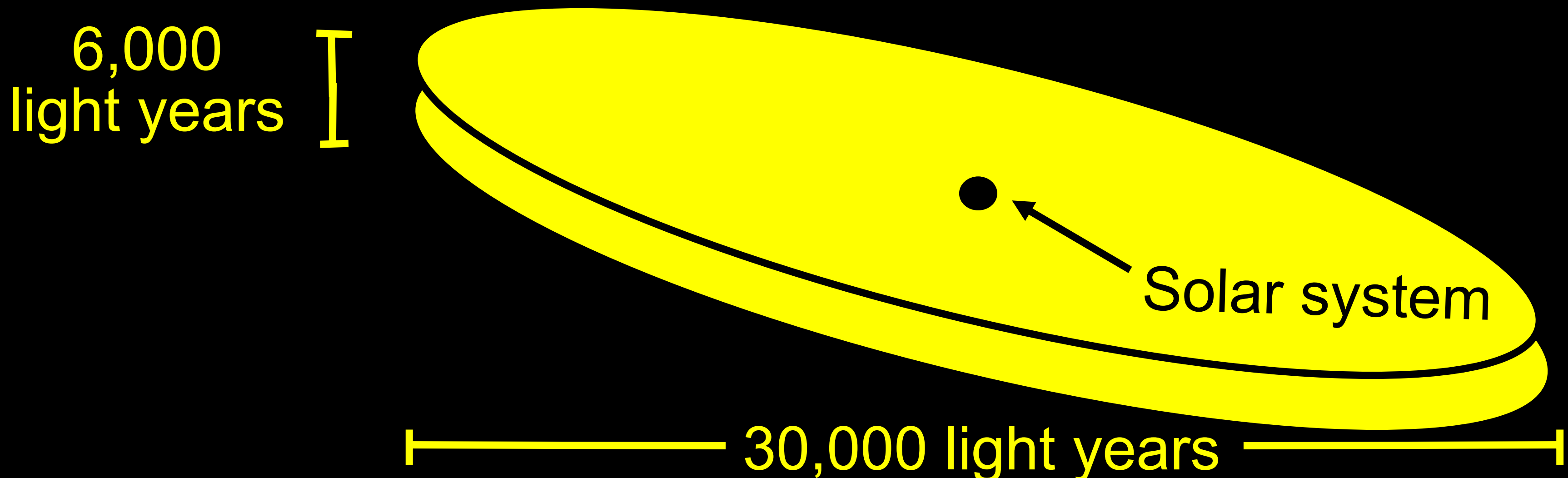
10,000 here →

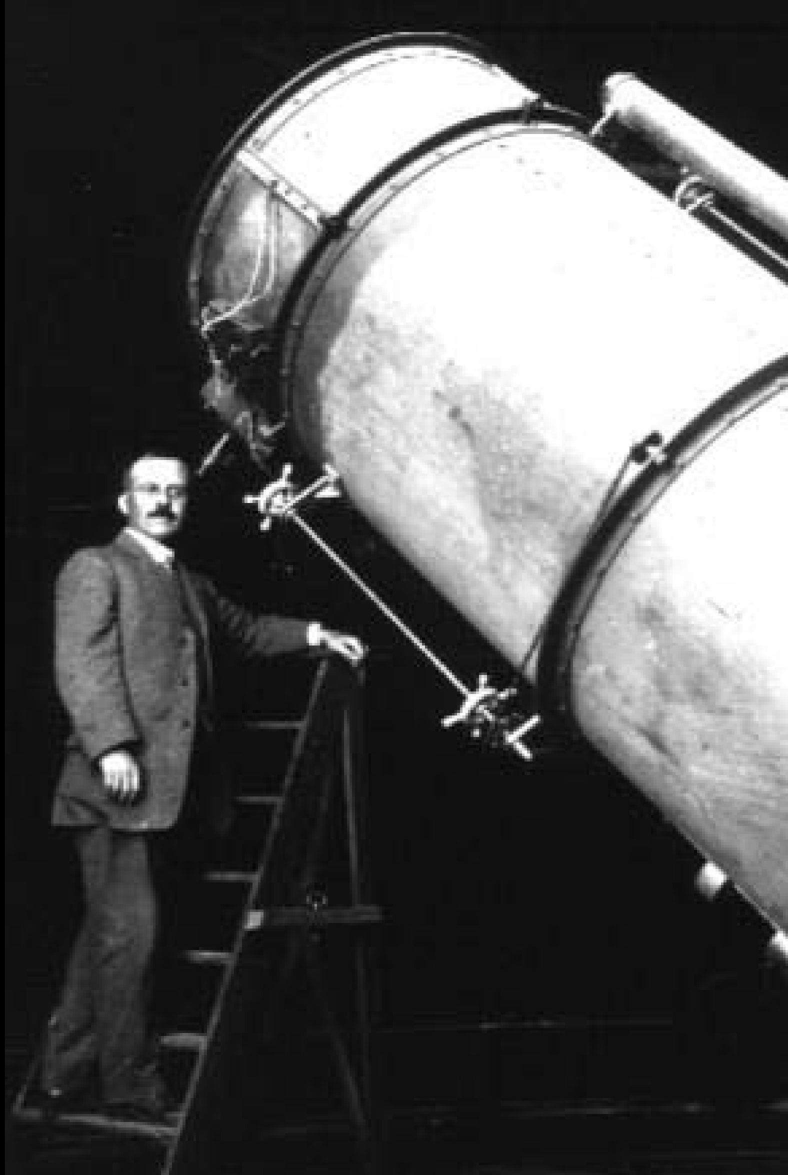
50 thousand million over entire sky



A view of the universe, circa 1906 A.D.

Kapteyn Universe





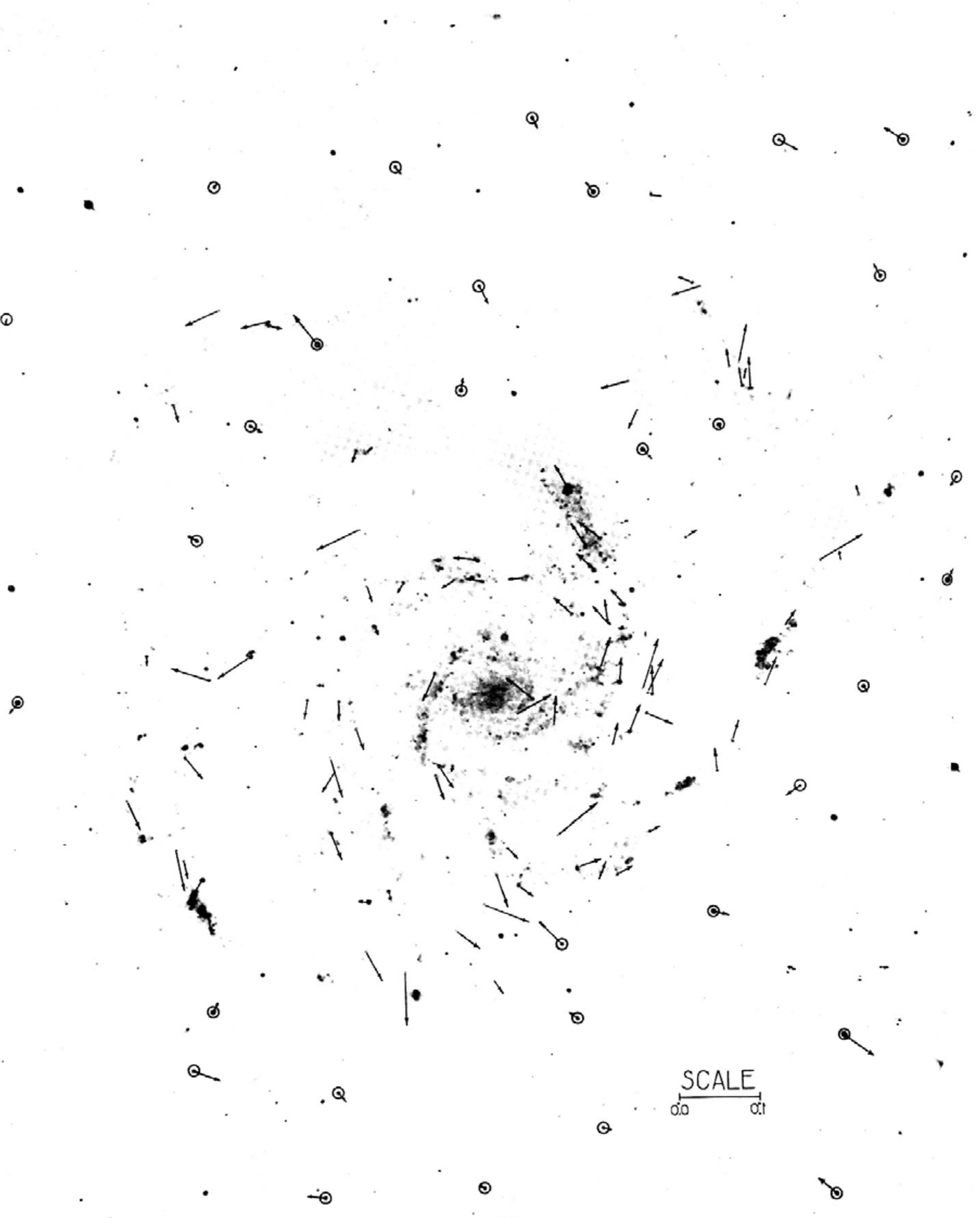
Heber Curtis
1872 - 1942

Harlow Shapley
1885 - 1972

Talking points in the Great Debate

1. Rotation of M101
2. Variable stars
3. Stars or gas
4. Spatial distribution & velocity

M101

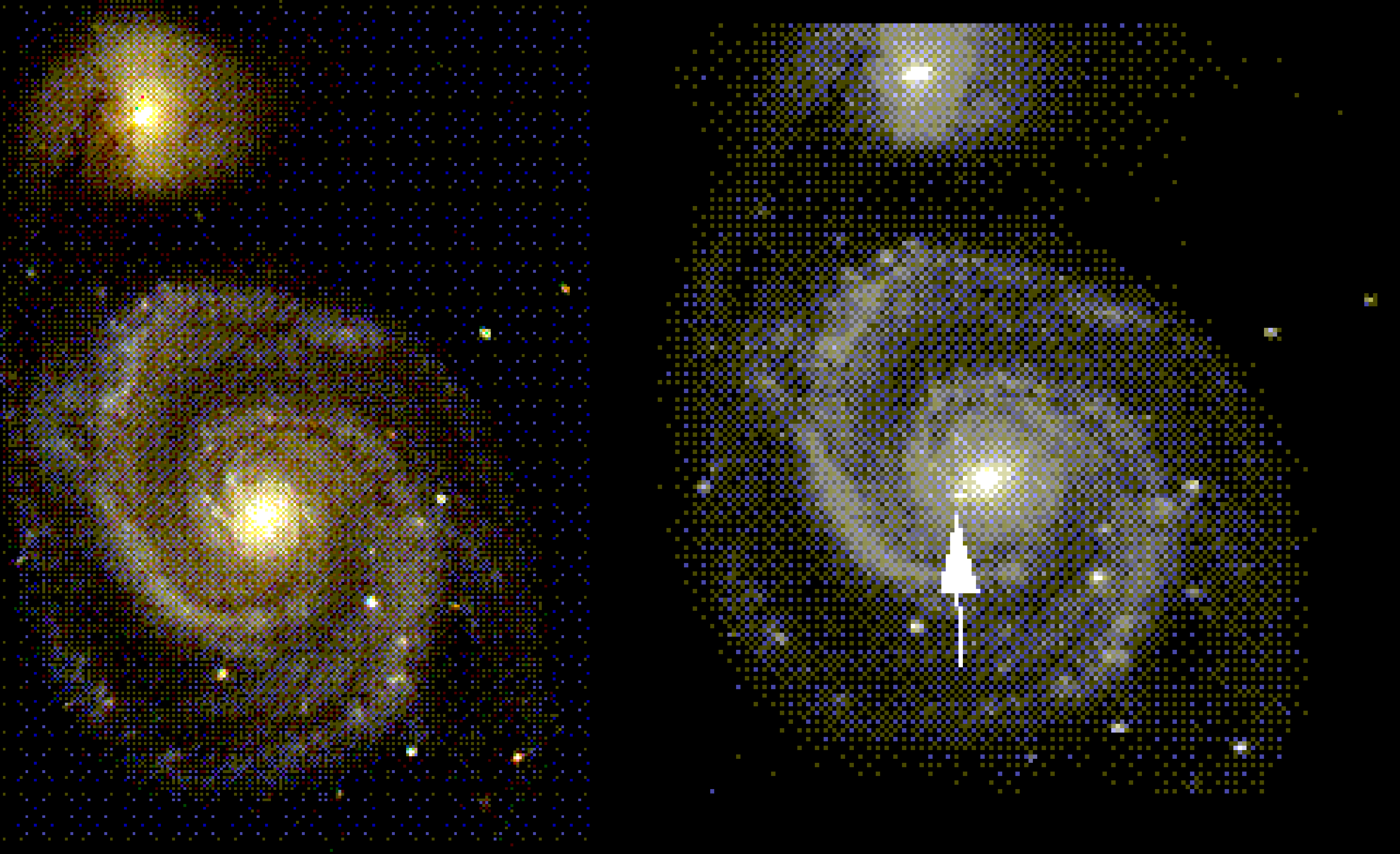


Adriaan van Maanen
1916

M101

Talking points in the Great Debate

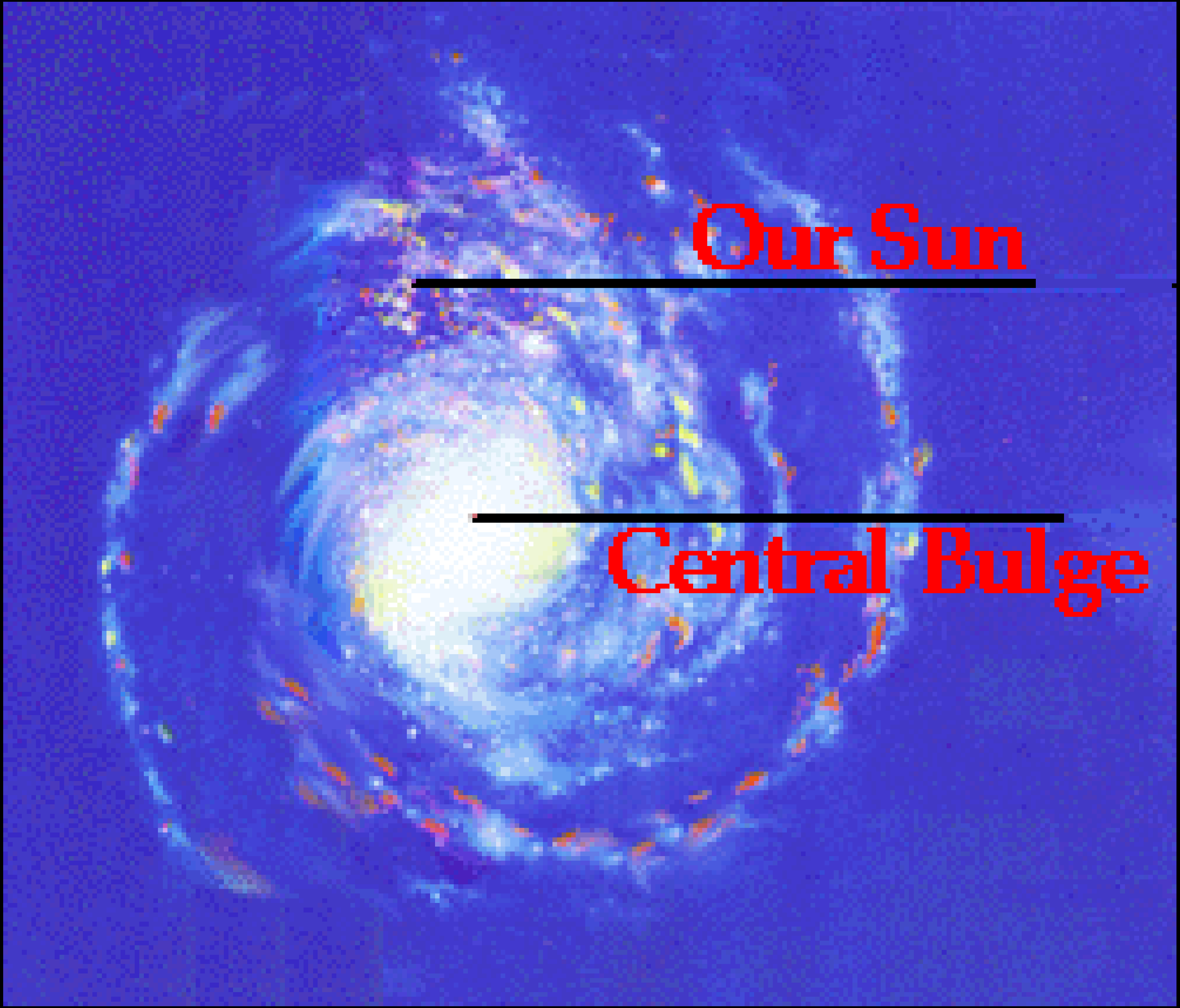
1. Rotation of M101
2. Variable stars
3. Stars or gas
4. Spatial distribution & velocity



Supernova in M51

Talking points in the Great Debate

1. Rotation of M101
2. Variable stars
3. Stars or gas
4. Spatial distribution & velocity



Our Sun
Central Bulge

Talking points in the Great Debate

1. Rotation of M101
2. Variable stars
3. Stars or gas
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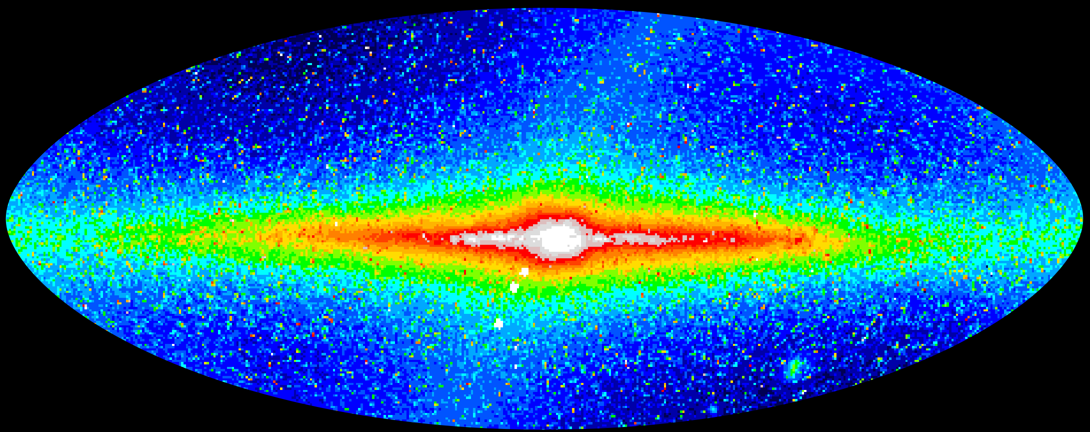


Dust in the galactic plane

Edwin Hubble
1884 - 1953

University of Chicago 1909 National Champions

University of Chicago 1909 Big-10 Champions

Track Team

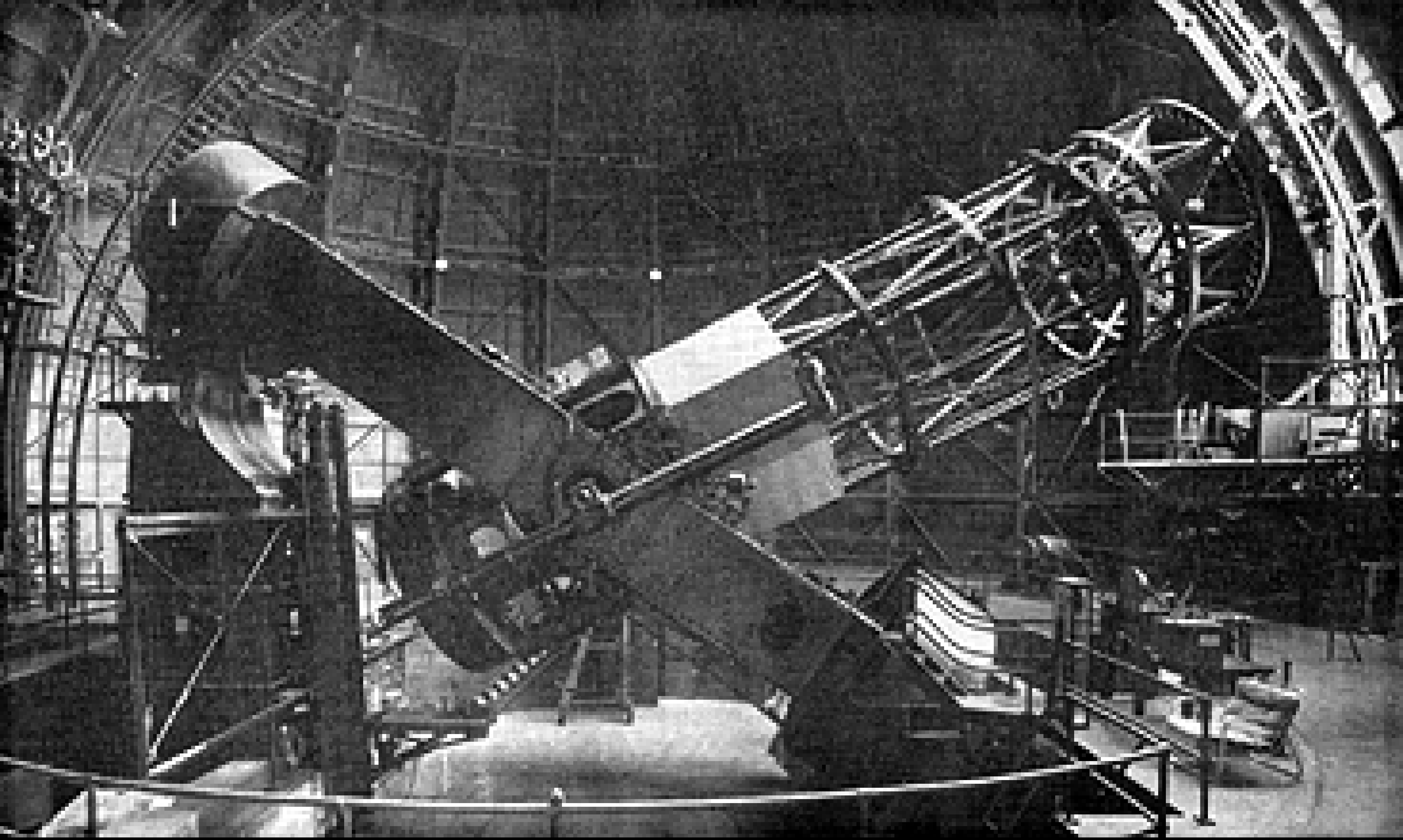


Two famous Rhodes Scholars:

Politics is for the moment; an equation is forever.

A. Einstein

Einstein at Yerkes, May 6, 1921



100-inch Hooker Telescope on Mt. Wilson

Hubble's Hooker Chair

TIME

THE WEEKLY NEWSMAGAZINE

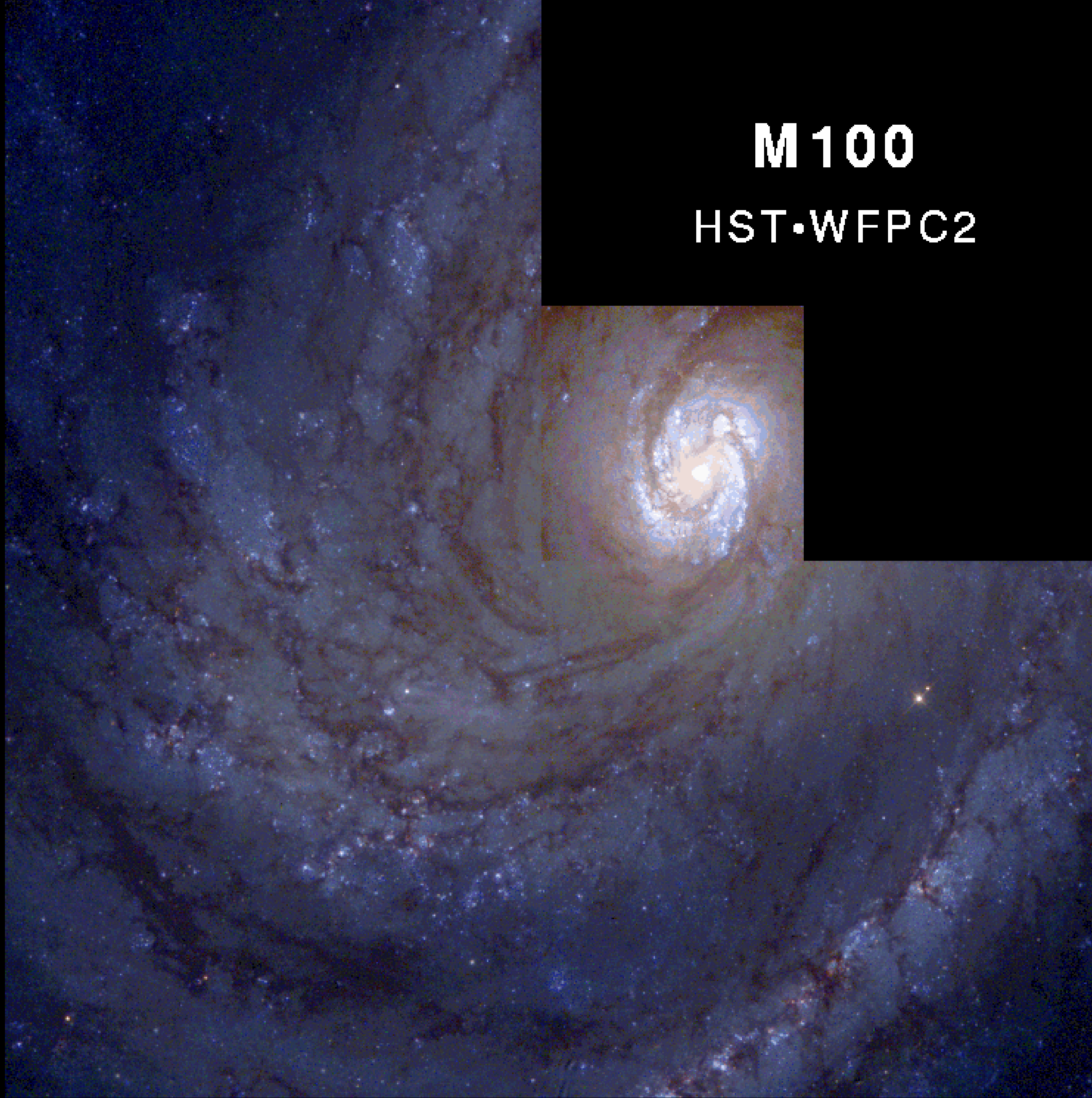
ASTRONOMER HUBBLE

Will Palomar's 200-inch eye see an exploding universe?

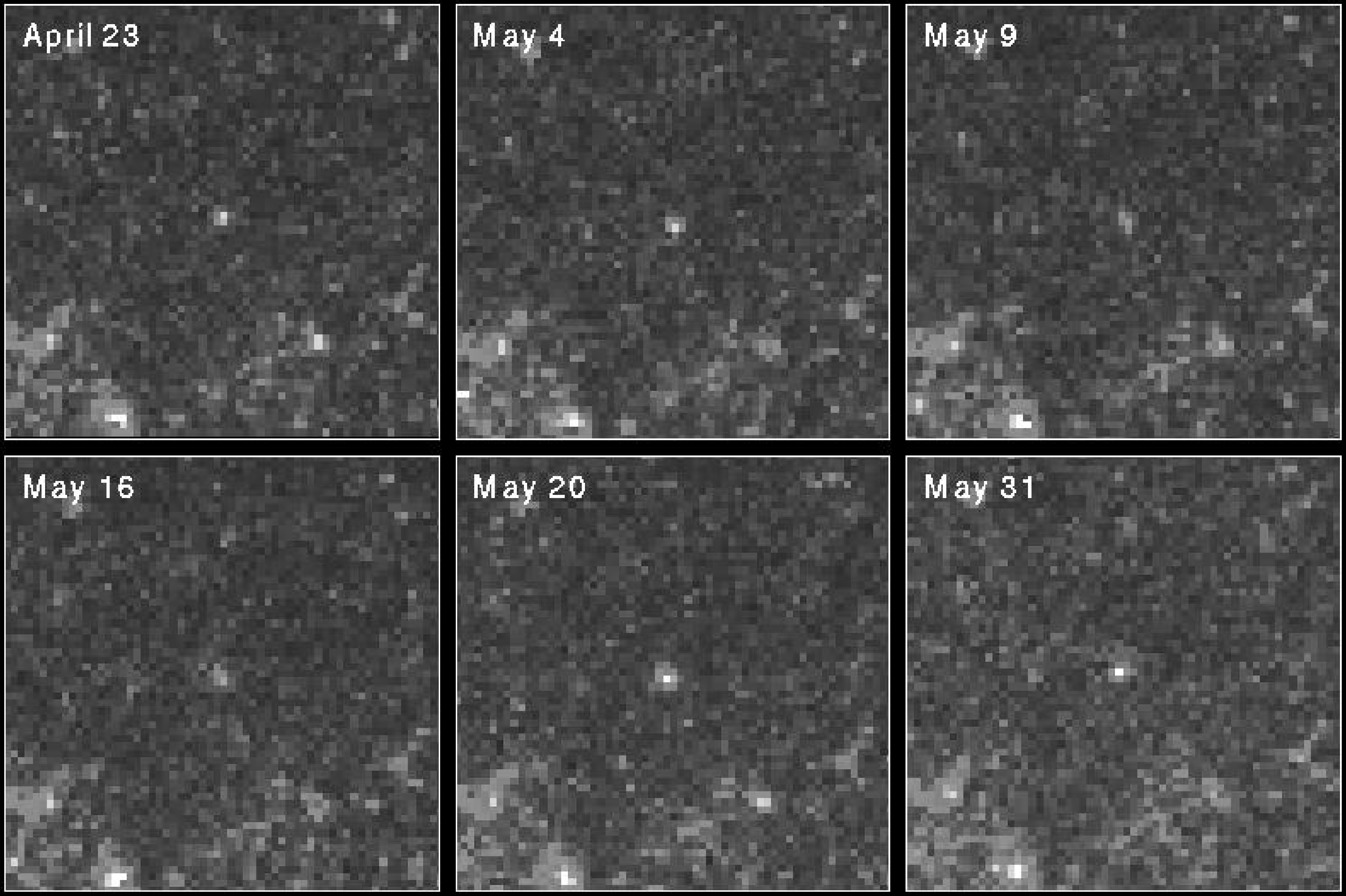
(Science)

ANDROMEDA
GALAXY


~~N~~
VAR!
N
6-Oct
1923
N


M100
HST•WFPC2

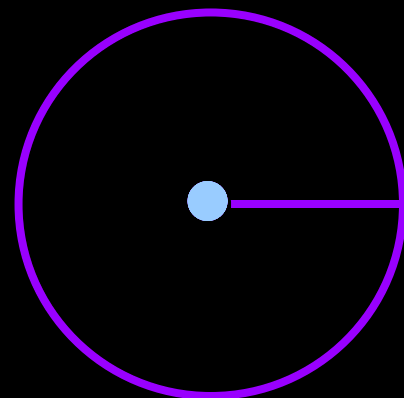
Cepheid Variable Star in Galaxy M100 HST•WFPC2



Redshift

t = 0

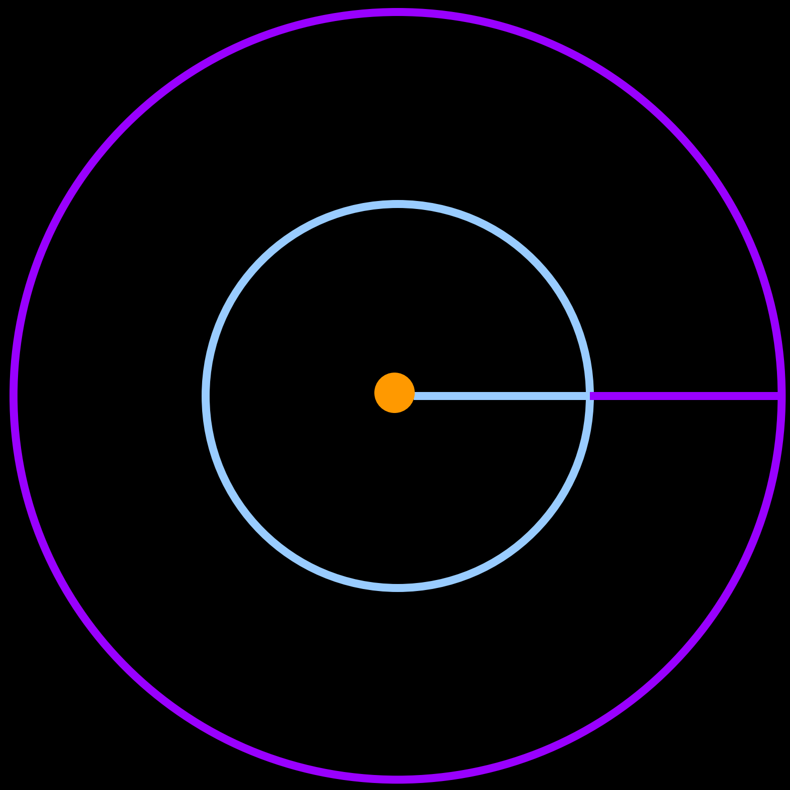
t = Δt

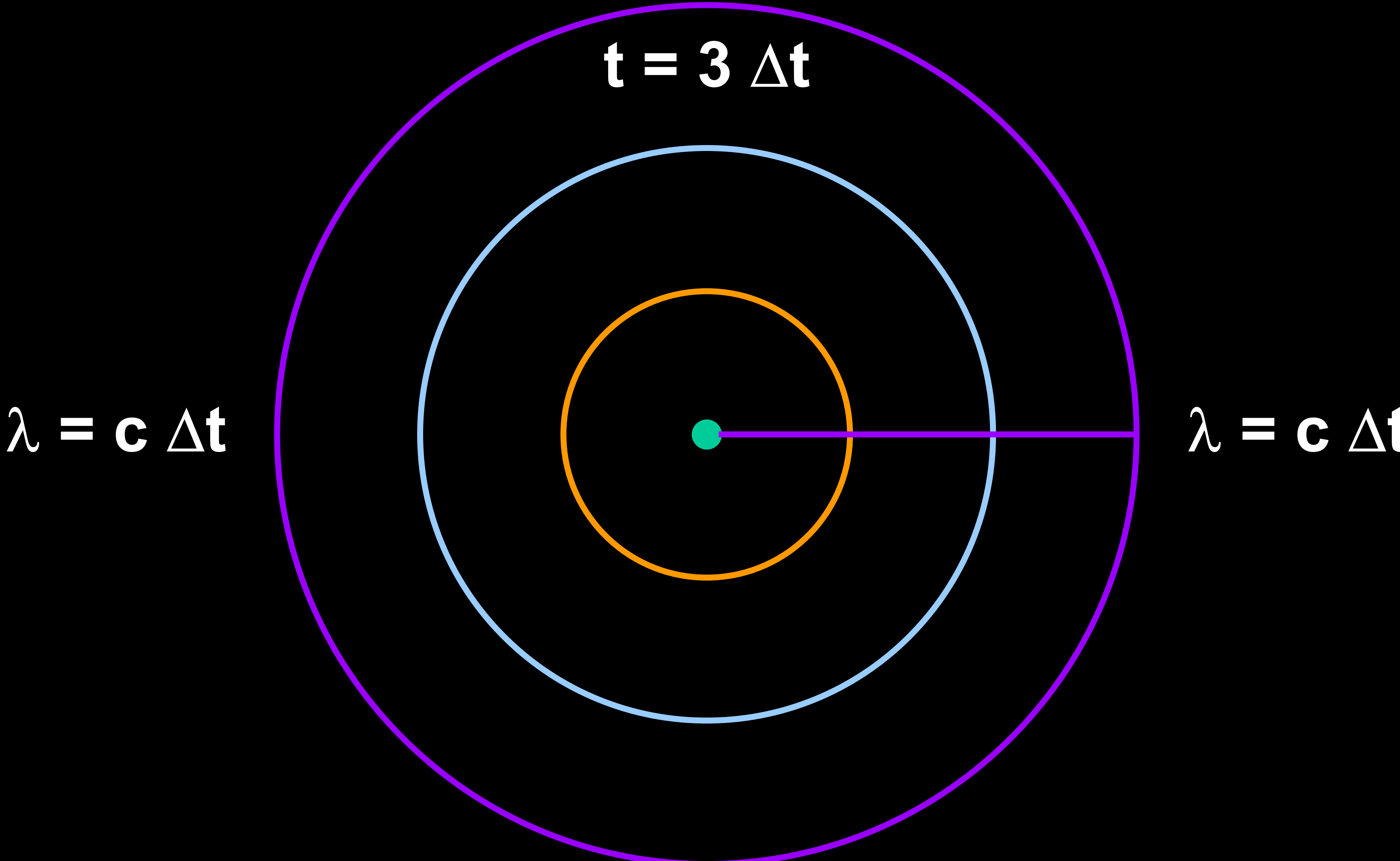


c = velocity of wave

Δt = time difference

$t = 2\ \Delta t$

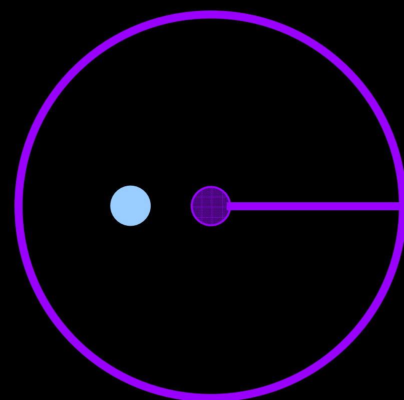




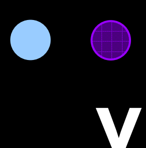
λ = distance between successive wavecrests

$t = 0$

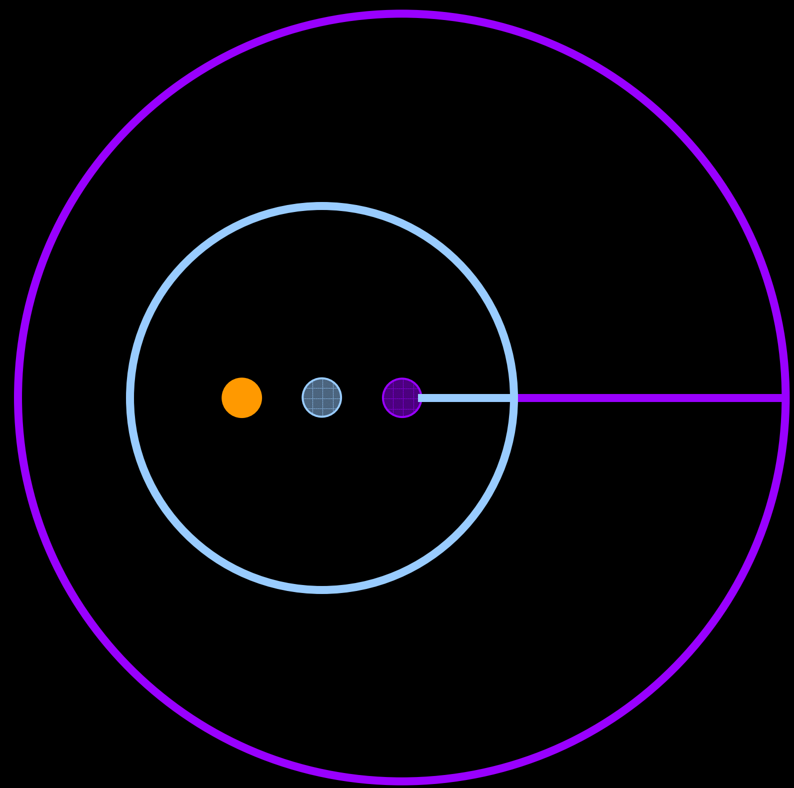
$t = \Delta t$



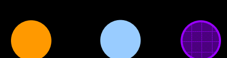
$d = v\,\Delta t$



$t = 2\,\Delta t$

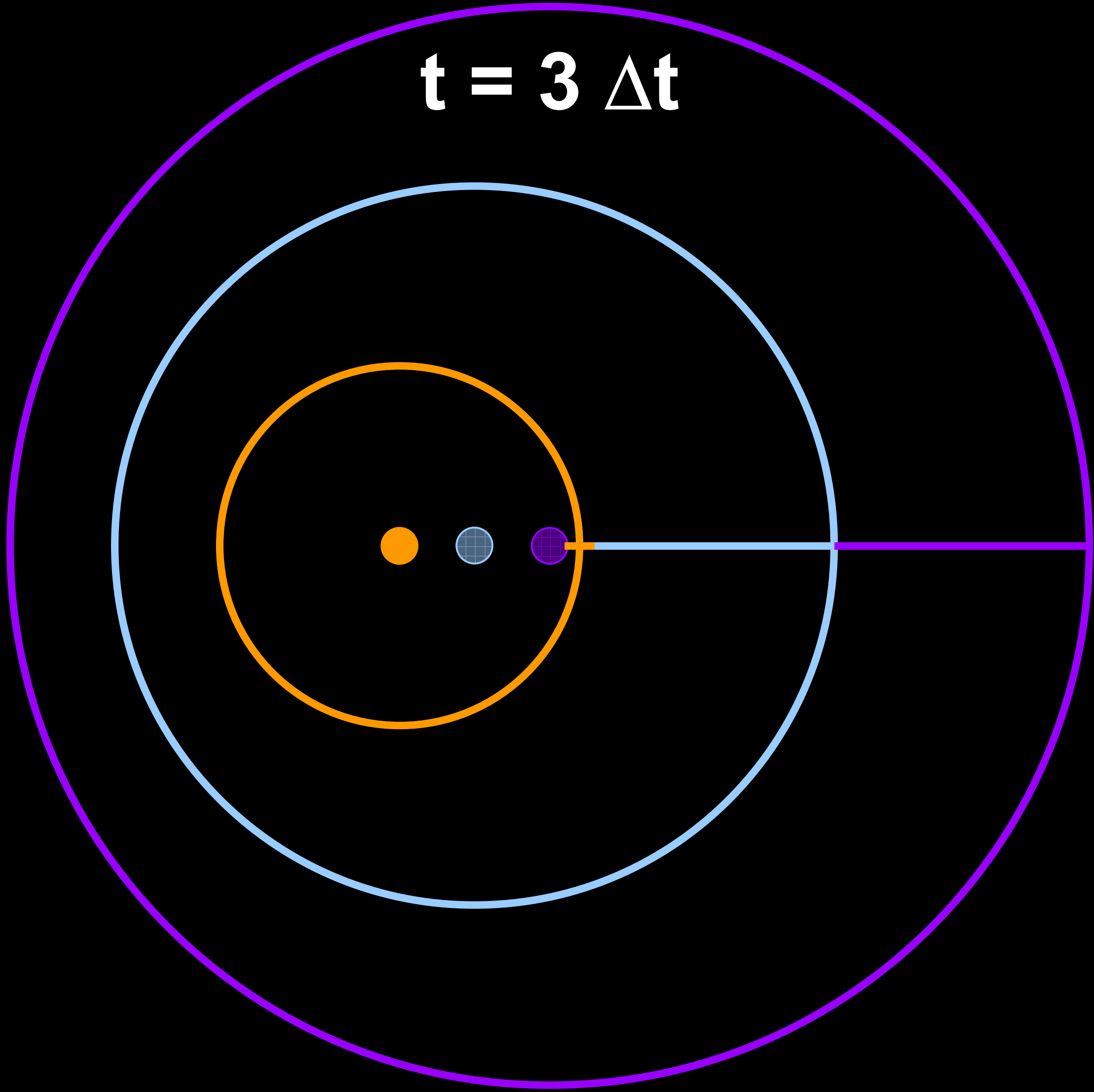


$d = v\,\Delta t$



v

$t = 3\,\Delta t$



$\lambda = c\,\Delta t$
$- v\,\Delta t$

$\lambda = c\,\Delta t$
$+ v\,\Delta t$

λ = distance between successive wavecrests

Doppler Shift

$$\lambda_0 = c\Delta t = \text{ rest wavelength}$$

$$\lambda = c\,\Delta t \pm \mathrm{v}\,\Delta t = \text{ detected wavelength}$$

$$c\,\Delta t = \lambda_0 \qquad \Rightarrow \qquad \lambda = \lambda_0 \pm \mathrm{v}\,\Delta t$$

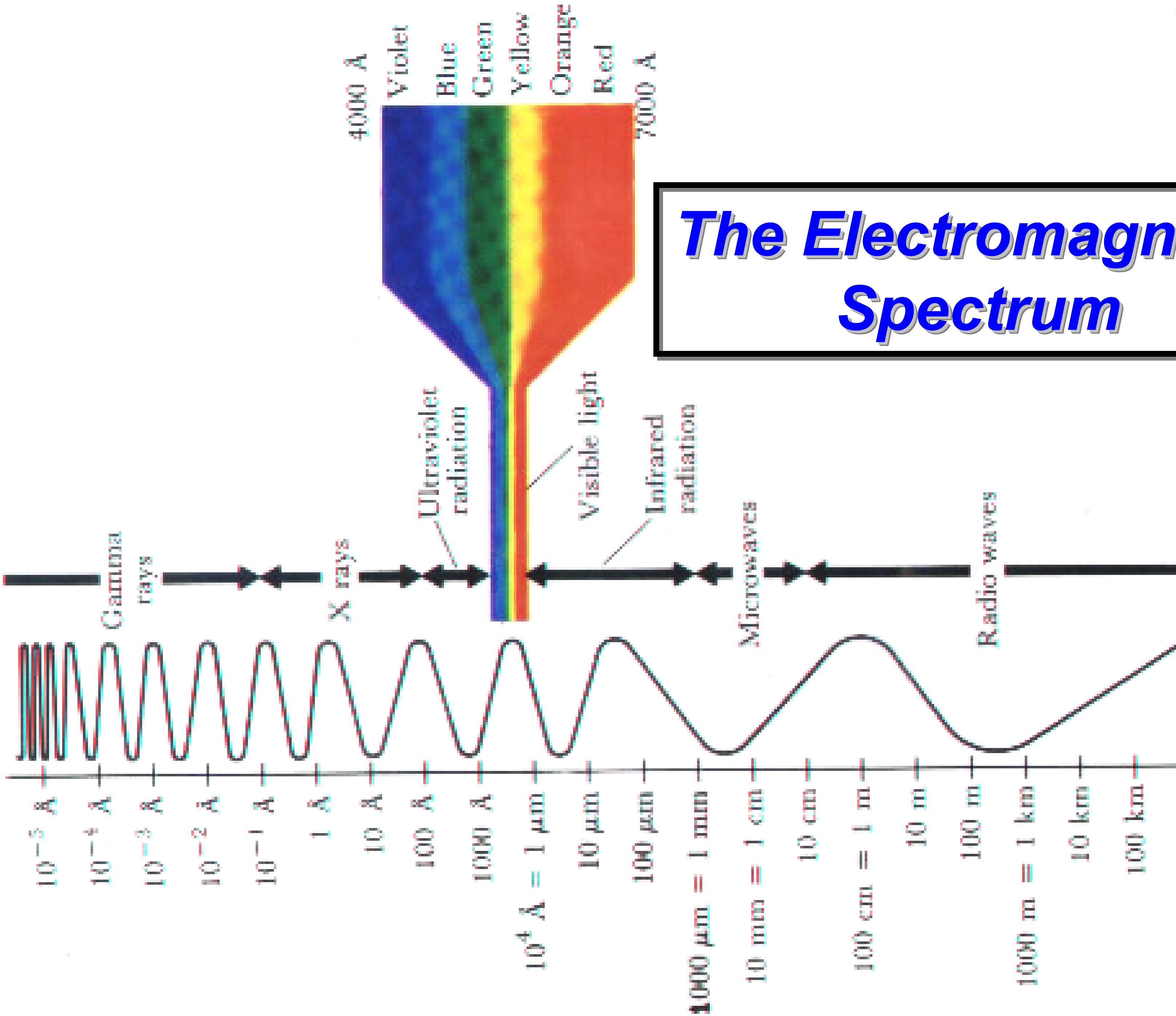
$$\Delta t = \frac{\lambda_0}{c} \qquad \Rightarrow \qquad \lambda = \lambda_0 \pm \frac{\mathrm{v}}{c}\lambda_0$$

$$\boxed{\lambda = \lambda_0\left(1 \pm \frac{\mathrm{v}}{c}\right)}$$

$+ \rightarrow$ receding (longer λ)

$- \rightarrow$ approaching (shorter λ)

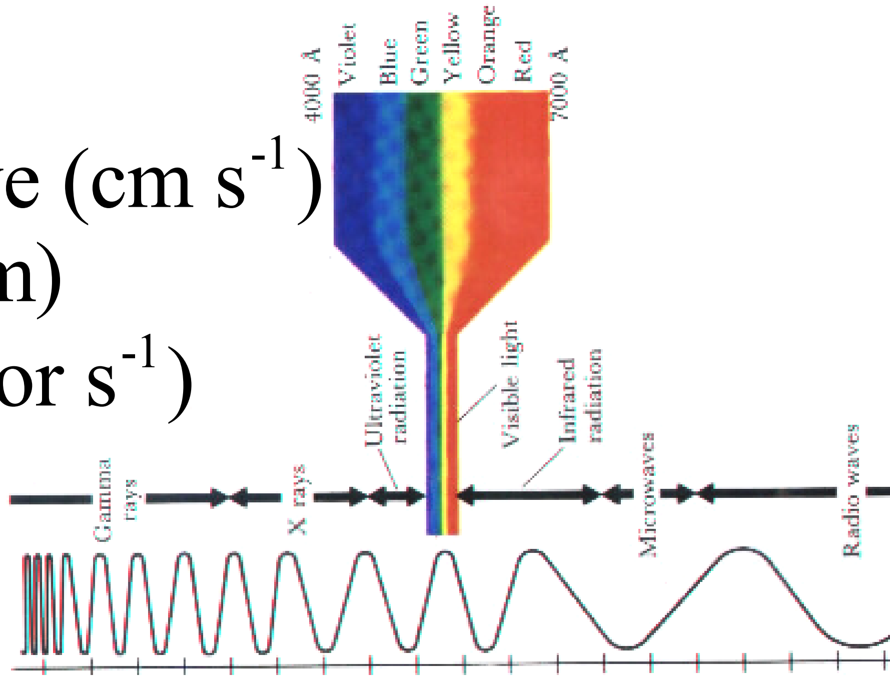
The Electromagnetic Spectrum

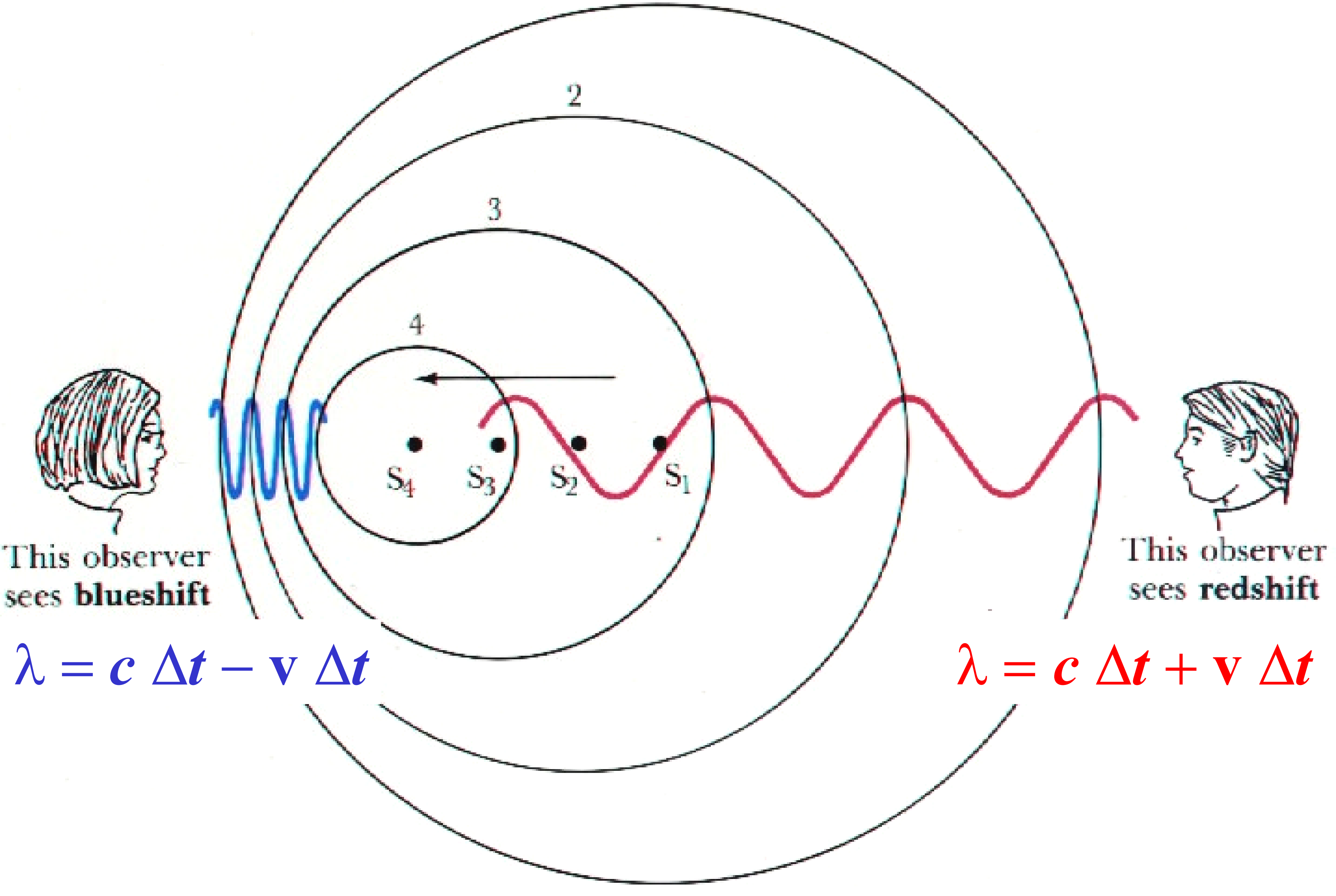


Facts about light

1. Light is a wave

$$c = \lambda \nu \quad \begin{cases} c = \text{ velocity of wave (cm s}^{-1}\text{)} \\ \lambda = \text{ wavelength (cm)} \\ \nu = \text{ frequency (Hz or s}^{-1}\text{)} \end{cases}$$





$\lambda = c\,\Delta t - v\,\Delta t$

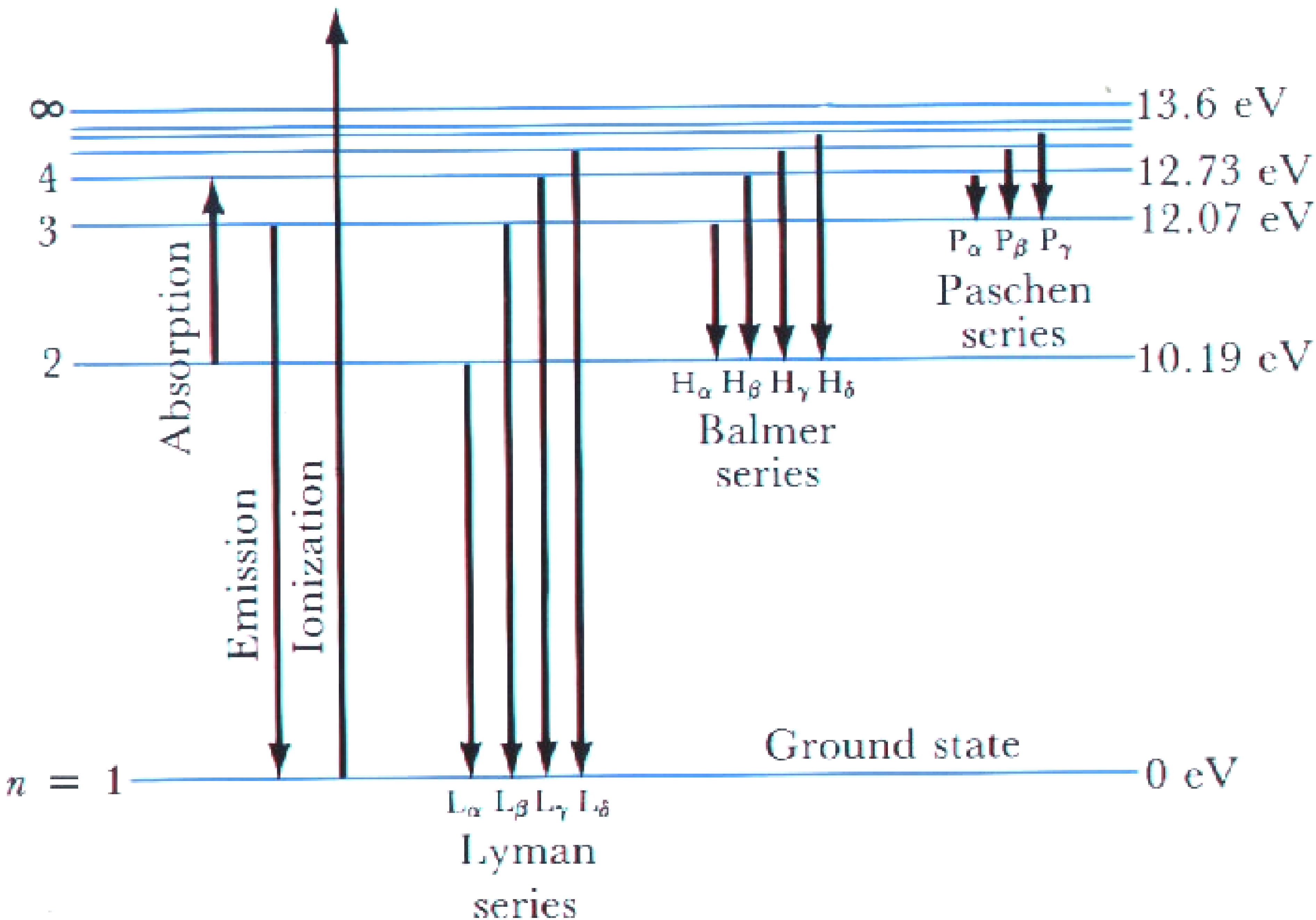
$\lambda = c\,\Delta t + v\,\Delta t$

Nothing exists but atoms and empty space; everything else is opinion.

- Demokritos

Everything has been thought of before. The problem is to think of it again.

- Goethe

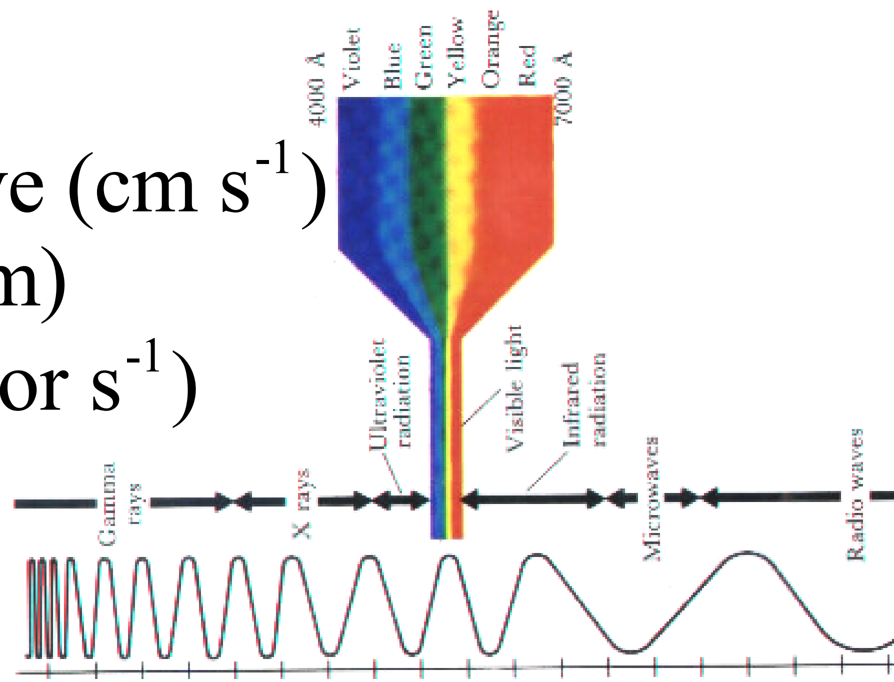


∞
4
3
2
n = 1
13.6 eV
12.73 eV
12.07 eV
10.19 eV
0 eV
Absorption
Emission
Ionization
Lα Lβ Lγ Lδ
Lyman series
Hα Hβ Hγ Hδ
Balmer series
Pα Pβ Pγ
Paschen series
Ground state

Facts about light

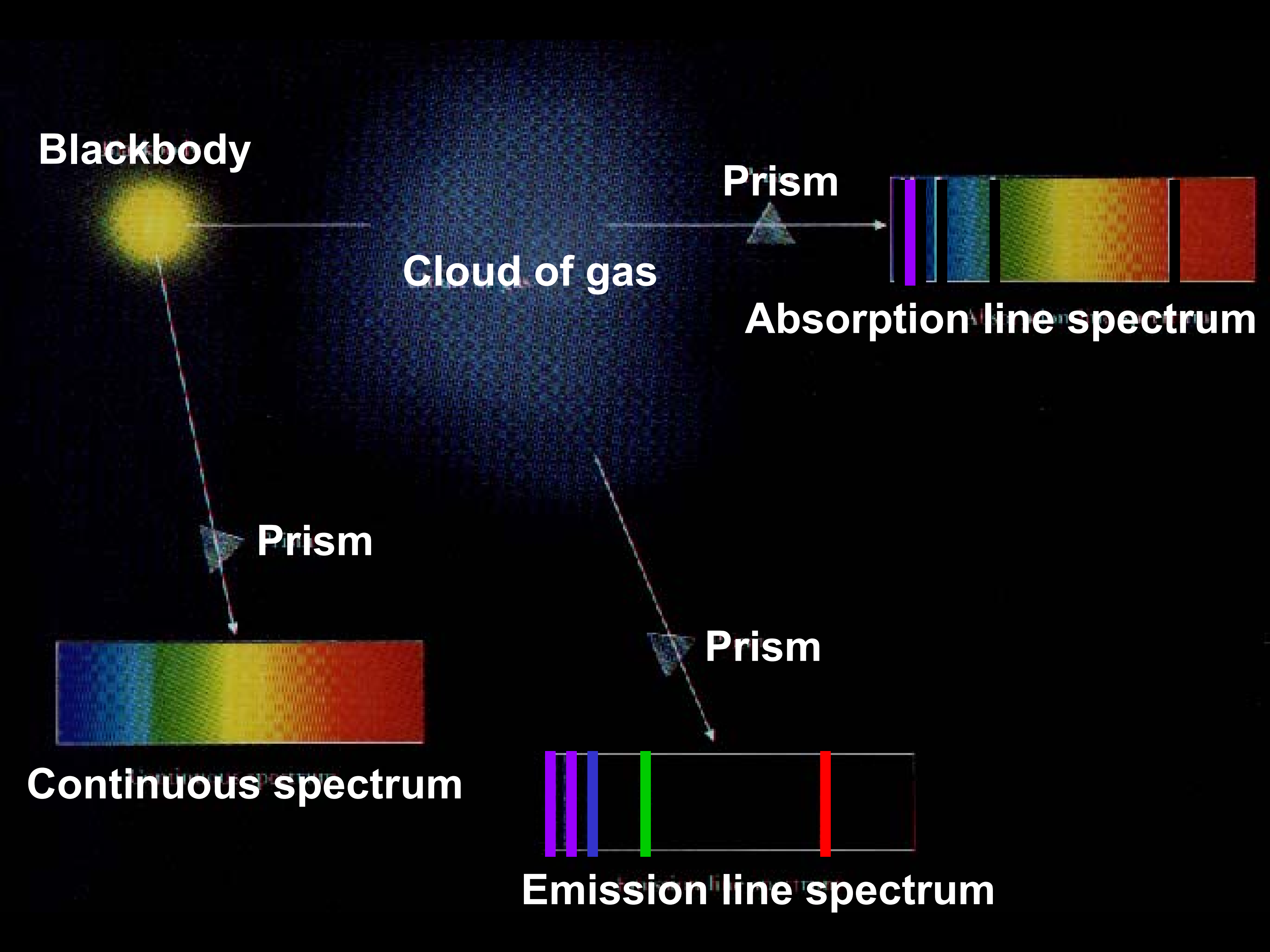
1. Light is a wave

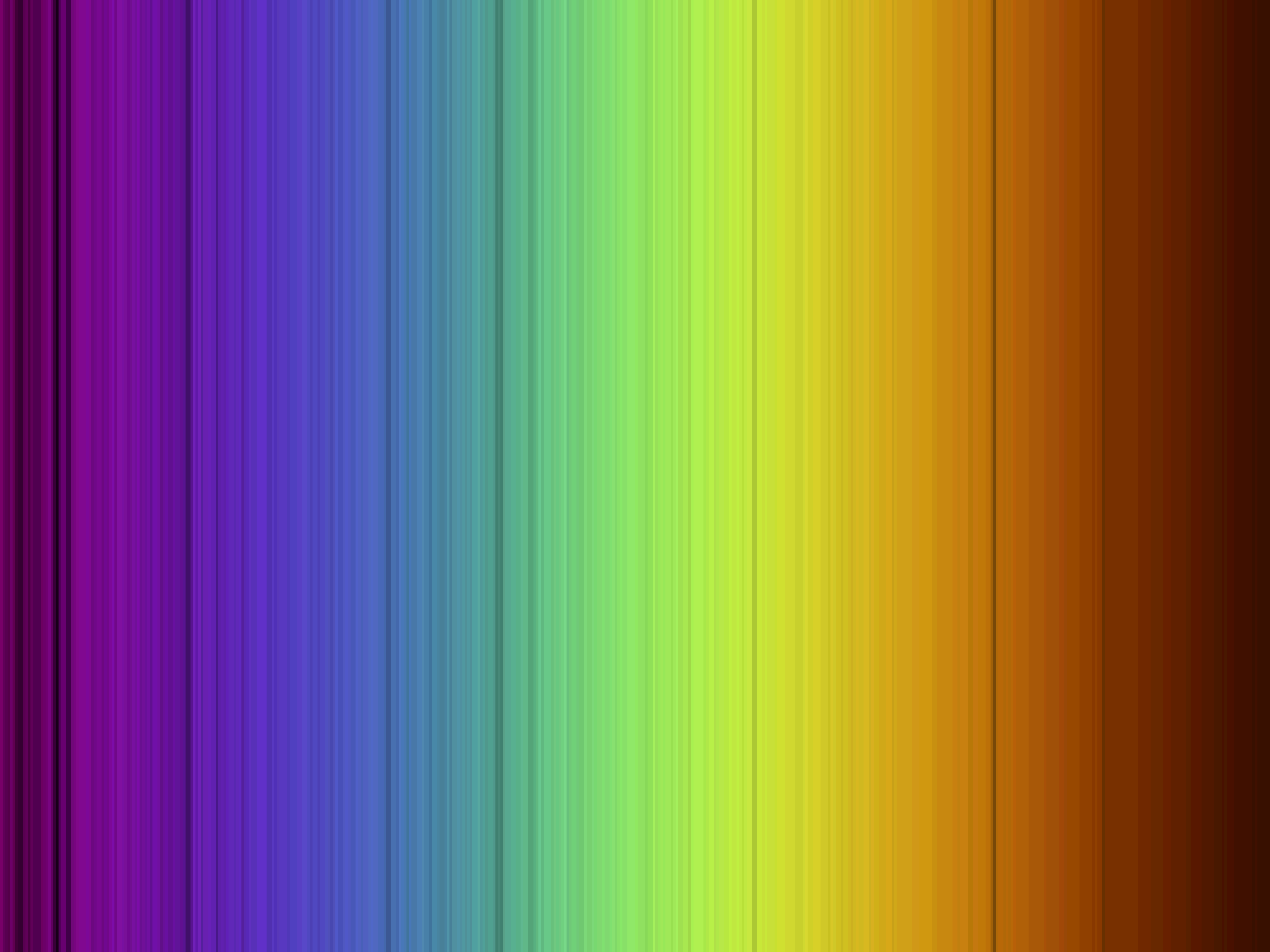
$$c = \lambda \nu \quad \begin{cases} c = \text{ velocity of wave (cm s}^{-1}\text{)} \\ \lambda = \text{ wavelength (cm)} \\ \nu = \text{ frequency (Hz or s}^{-1}\text{)} \end{cases}$$

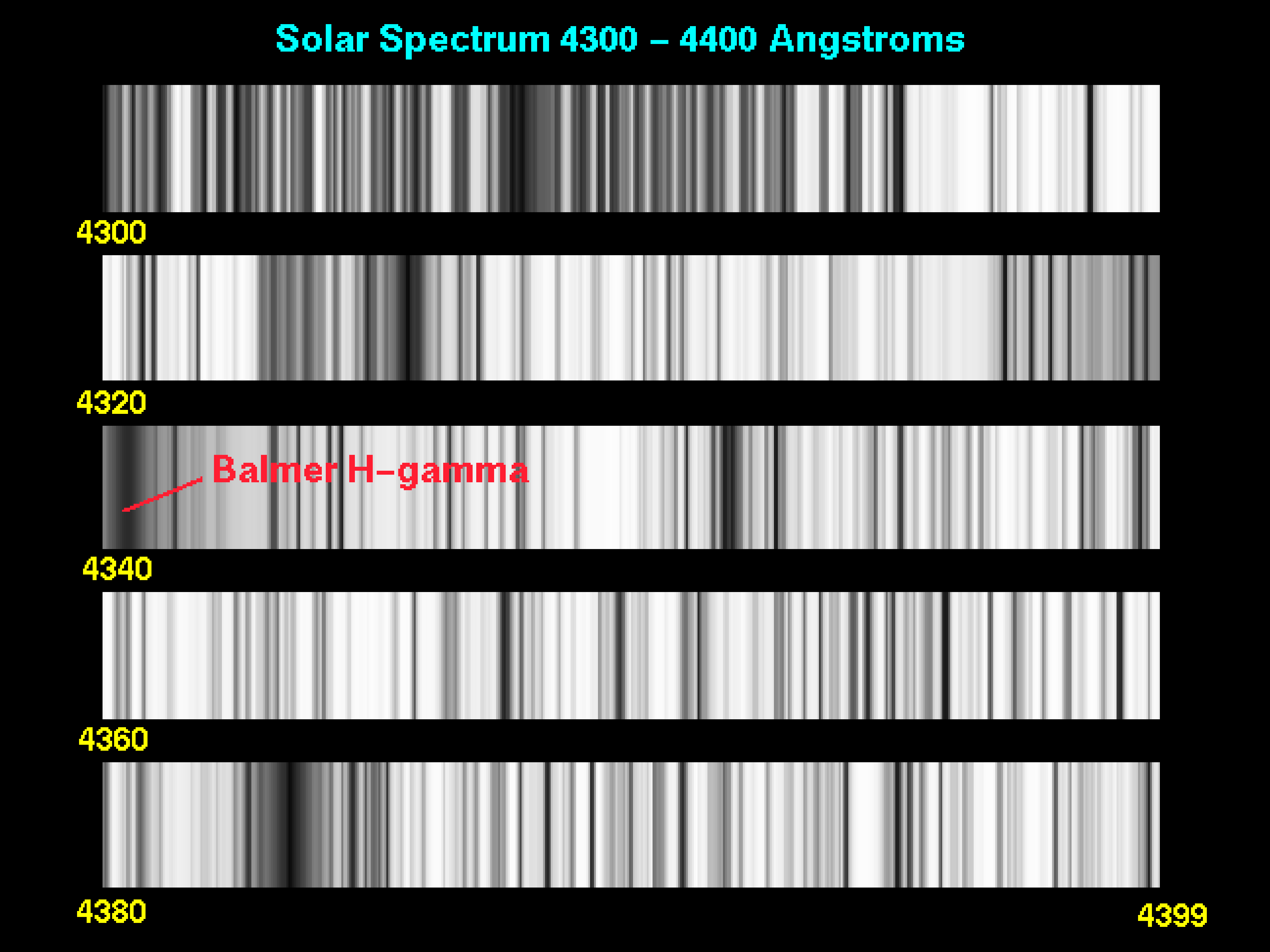


2. The wavelength is quantized

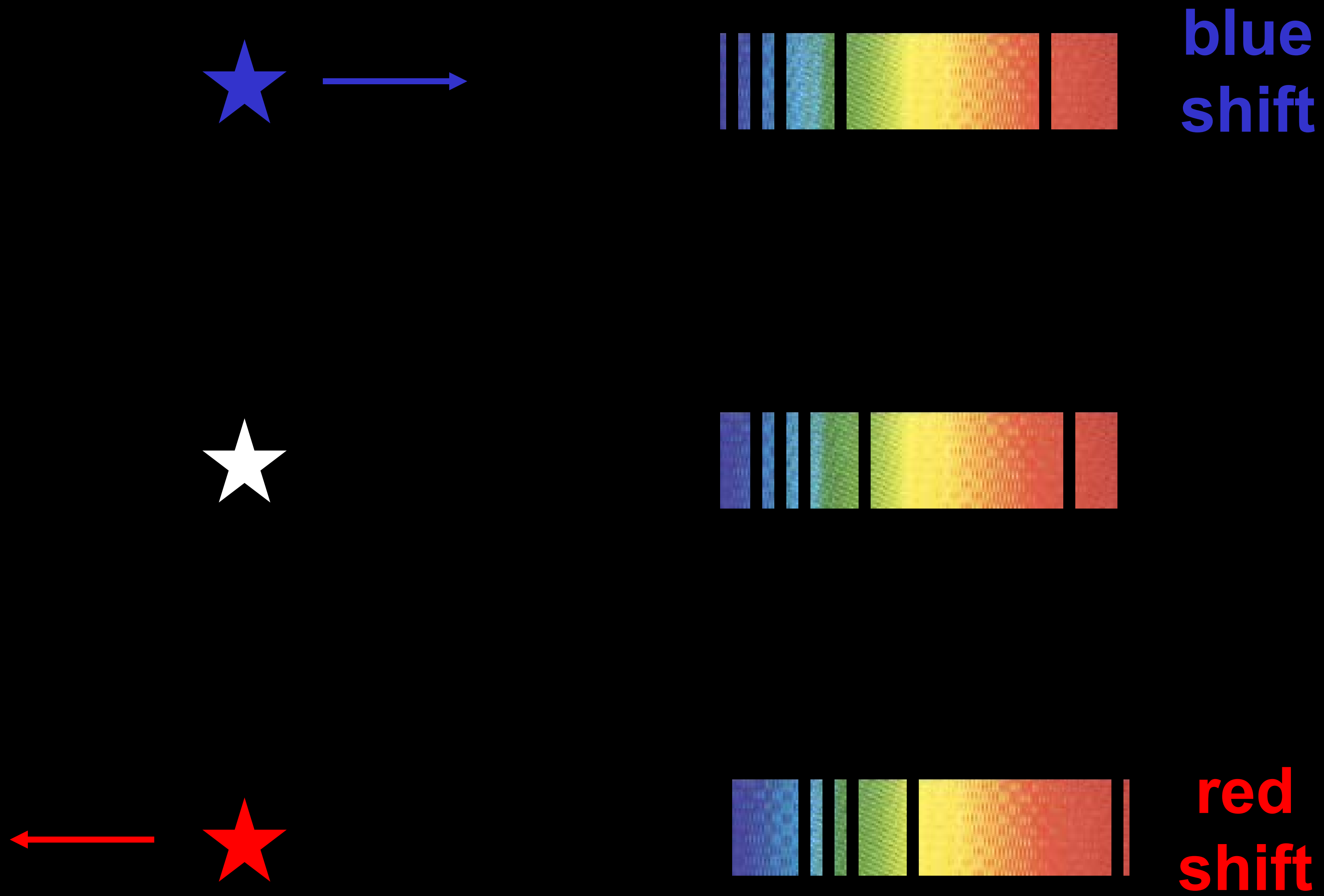
Visible Emission Spectrum


Blackbody
Cloud of gas
Prism
Absorption line spectrum
Prism
Continuous spectrum
Prism
Emission line spectrum





Solar Spectrum 4300 – 4400 Angstroms
4300
4320
Balmer H–gamma
4340
4360
4380
4399


blue
shift
red
shift

Edwin Hubble
1884 - 1953

The **red** **shift**

$$\boxed{\frac{\lambda}{\lambda_0} = 1 + \frac{\mathrm{v}}{c}}$$

λ **detected wavelength**

λ_0 **emitted wavelength**

v **recessional velocity**

c **velocity of light**

$$\boxed{\frac{\lambda}{\lambda_0} - 1 = \frac{\mathrm{v}}{c}}$$

$$c = 3 \times 10^5 \ \mathrm{km\ s^{-1}}$$

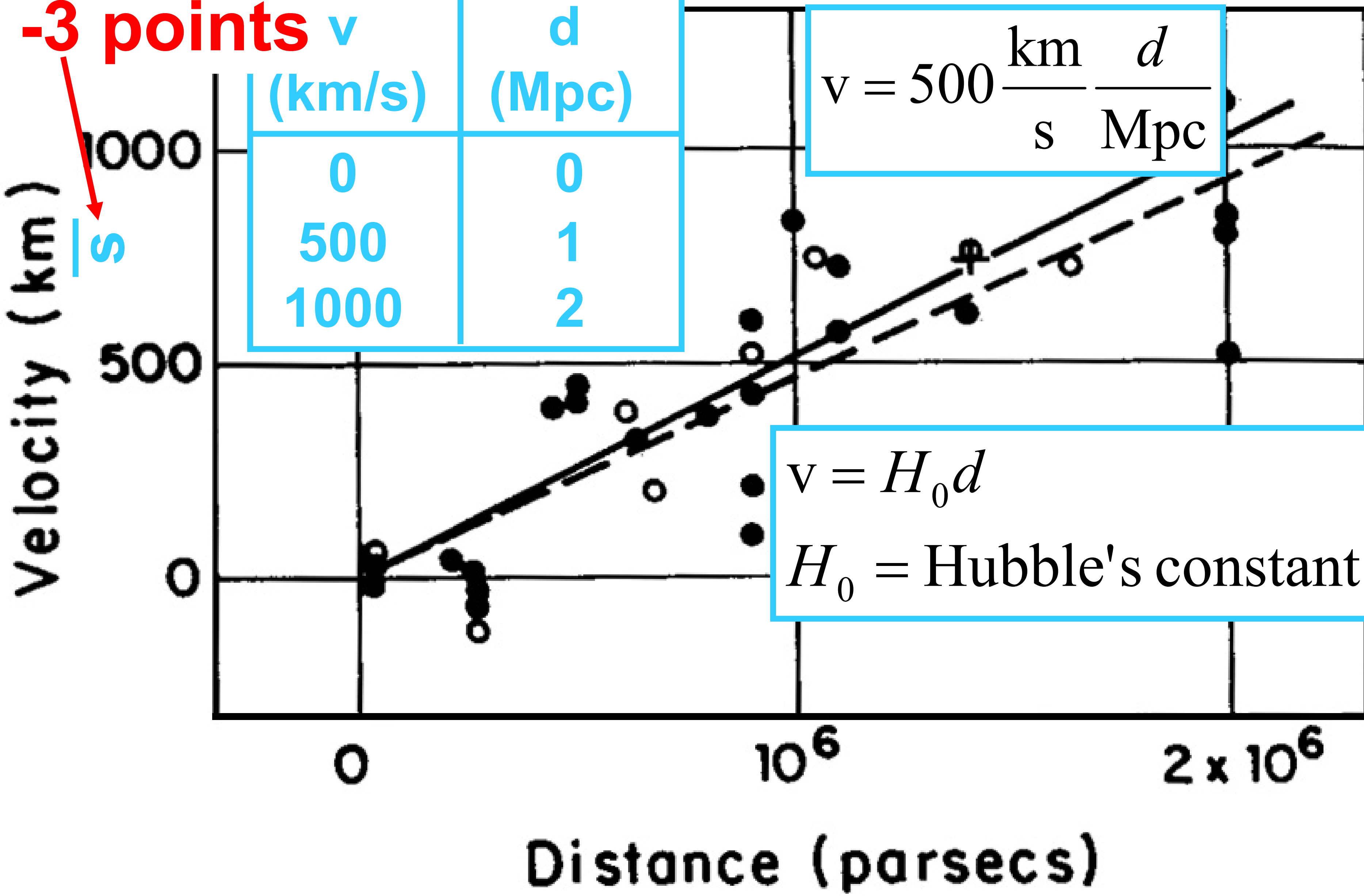
$$(\lambda > \lambda_0)$$

Hubble's Discovery Paper - 1929

-3 points

v (km/s)	d (Mpc)
0	0
500	1
1000	2

$$v = 500 \frac{\text{km}}{\text{s}} \frac{d}{\text{Mpc}}$$



$$v = H_0 d$$

$$H_0 = \text{Hubble's constant}$$

INSTANT

QUAKER OATMEAL®

With Real

Cinnamon & Spice

All Natural Flavors

FACT OR FICTION

SCIENCE

The universe is shrinking and will soon be the size of a golf ball.

See other side for answer.

CONVENTIONAL DIRECTIONS

Empty packet into bowl.
Add **1/2 cup** boiling water; stir.

MICROWAVE DIRECTIONS

Empty packet into microwaveable bowl.
Add **2/3 cup** water or milk.
Microwave at **HIGH** about 1-2 minutes; stir.
Use care when removing cereal from microwave; bowl may be hot.

For **thicker** oatmeal decrease liquid; for **thinner** oatmeal increase liquid.

THE ANSWER

Fiction! Most stars and galaxies are moving away from the earth which means the universe is actually getting bigger.

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All Natural Flavors

FACT OR FICTION

SCIENCE

Sir Isaac Newton discovered gravity by watching an apple fall.

See other side for answer.

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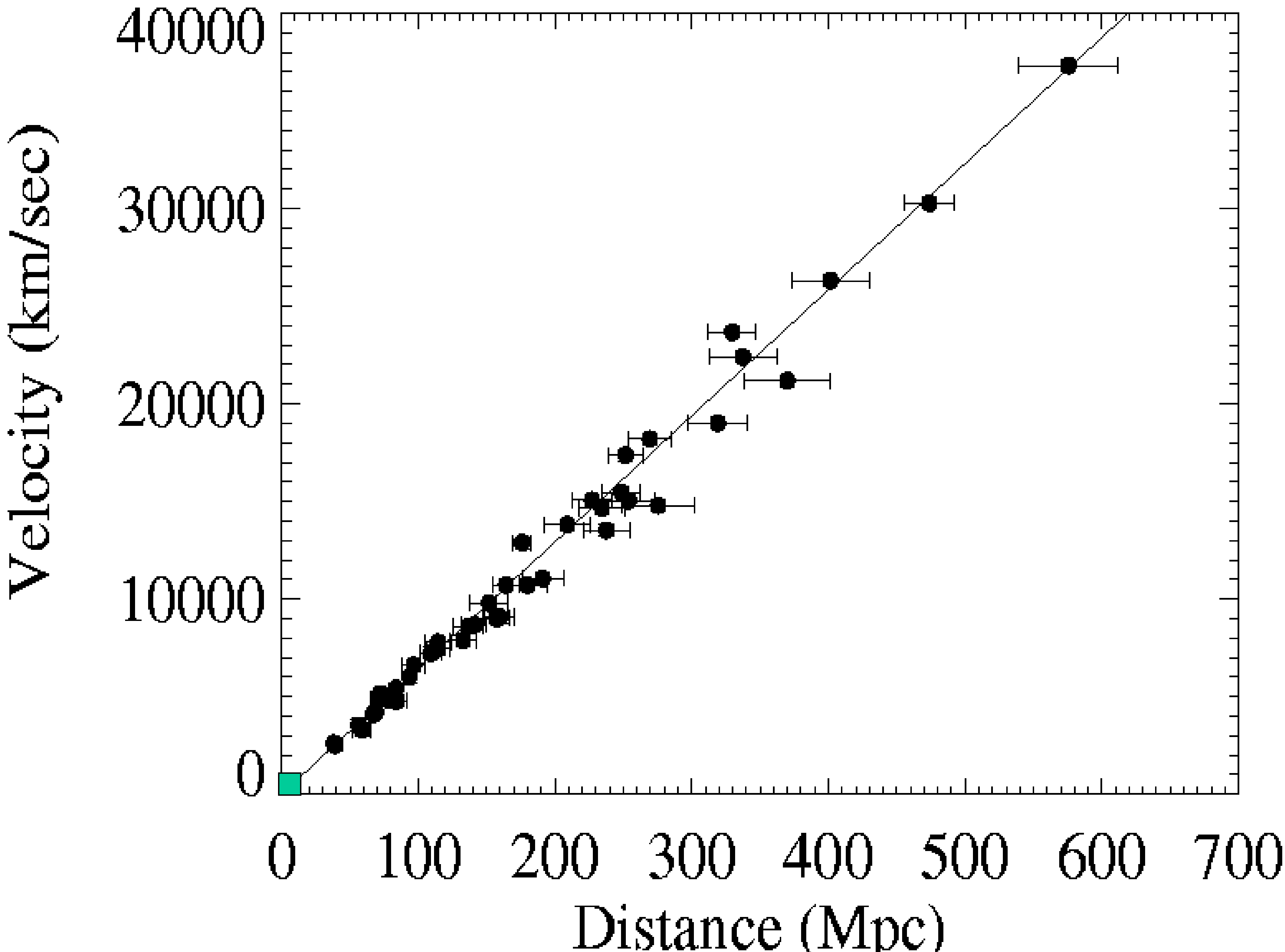
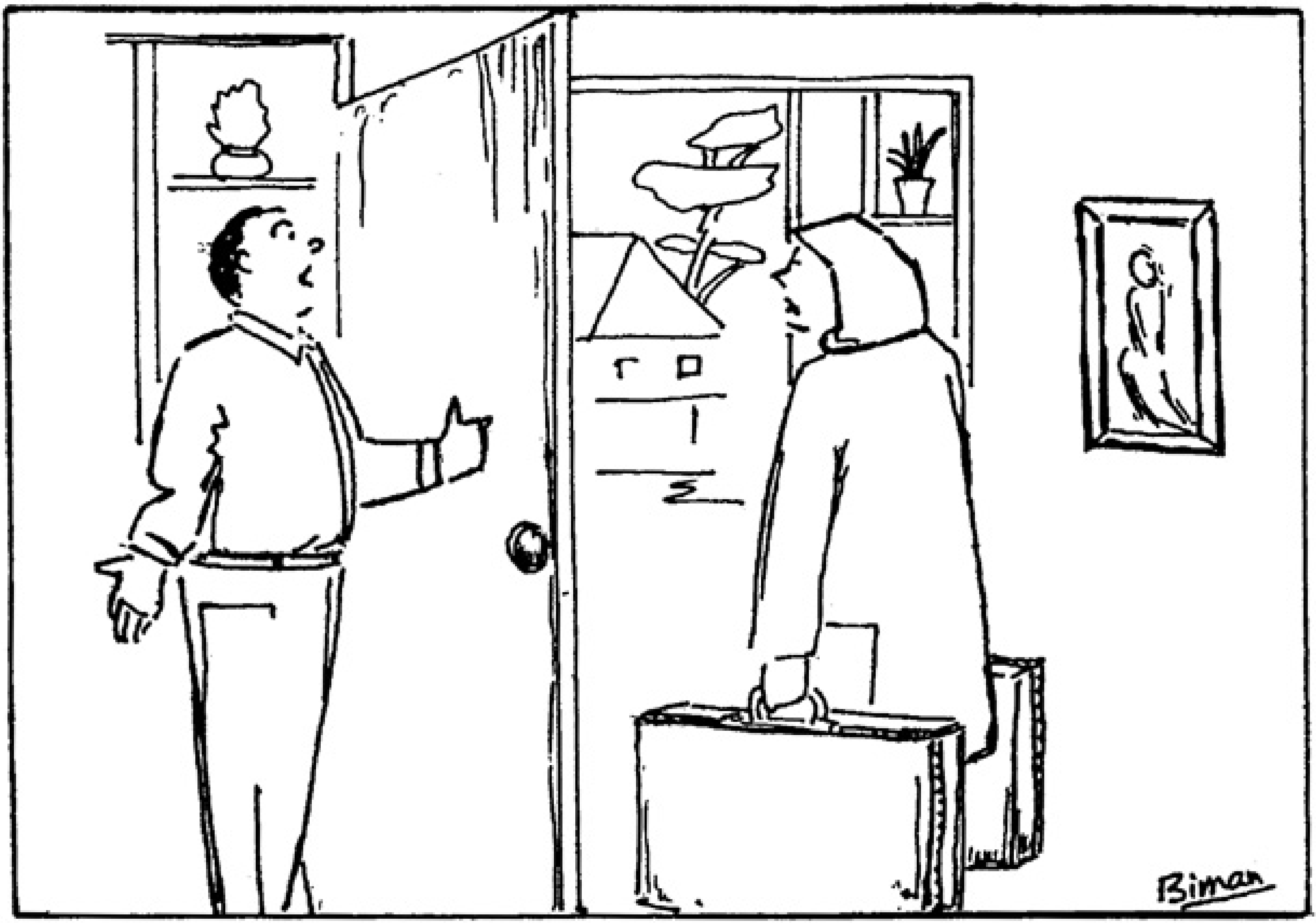
THE ANSWER

Fact! Newton made his famous discovery as a young man but was unable to prove it until almost 20 years later.

P.O. Box 9003, Chicago, IL 60650-9003



40000
30000
20000
10000
0
Velocity (km/sec)
0
100
200
300
400
500
600
700
Distance (Mpc)



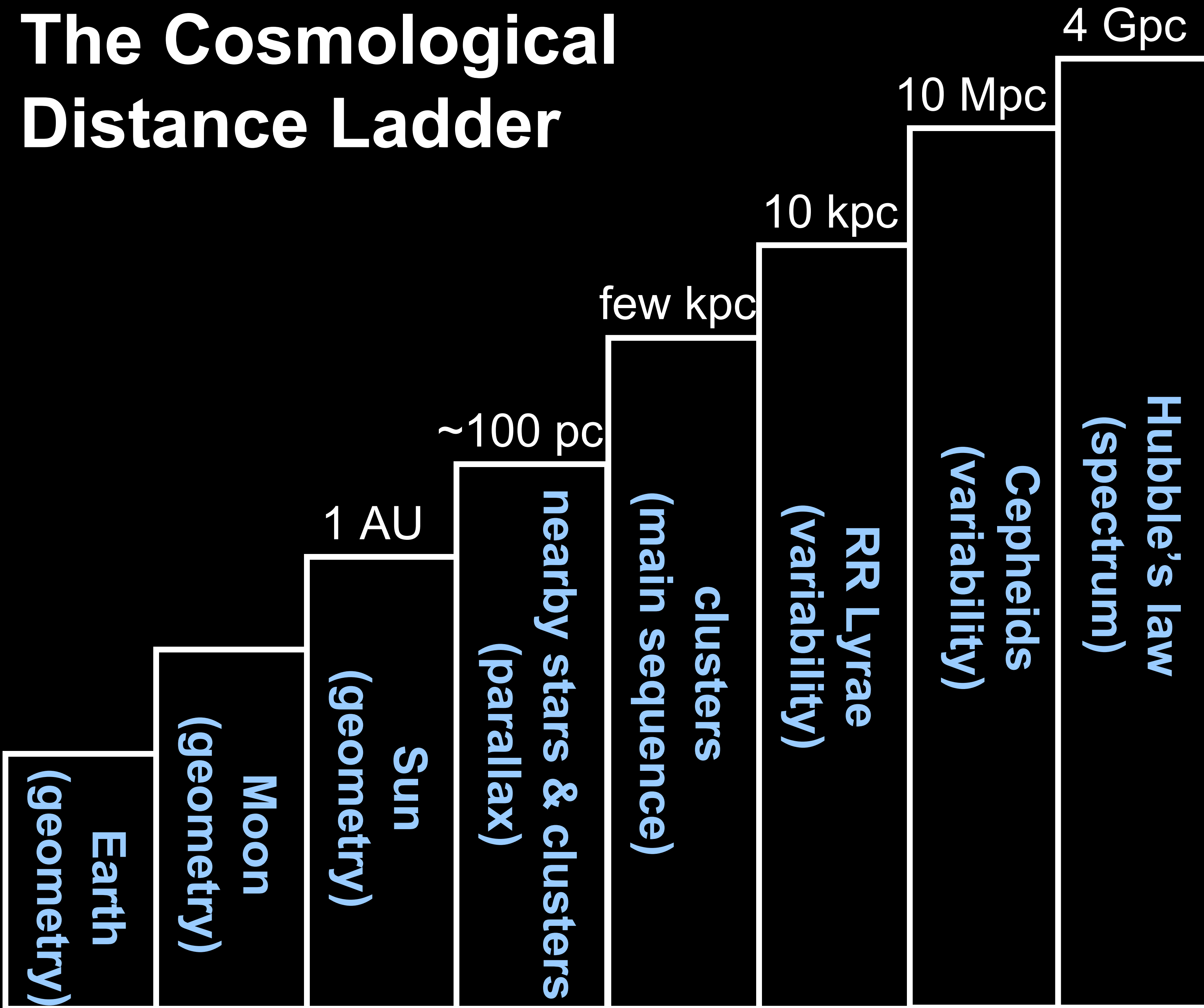
"THE HUBBLE CONSTANT? I WOULDN'T HAVE THOUGHT <u>THAT</u> WOULD EVER COME BETWEEN US!"

$$\mathrm{v} = H_0 d$$

$$H_0 = \text{Hubble's constant}$$

$H_0 = 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$	**Hubble**	**1929**
$H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$		**1960s**
$H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$		**1970s**
$H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$		**1990s**
$H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$		**2001**

The Cosmological Distance Ladder



Doppler Shift

$$\lambda_0 = \text{rest wavelength}$$

$$\lambda = \text{detected wavelength}$$

$$\boxed{\lambda = \lambda_0 \left(1 \pm \frac{\mathrm{v}}{c} \right)}$$

$+ \rightarrow$ receding (longer λ)

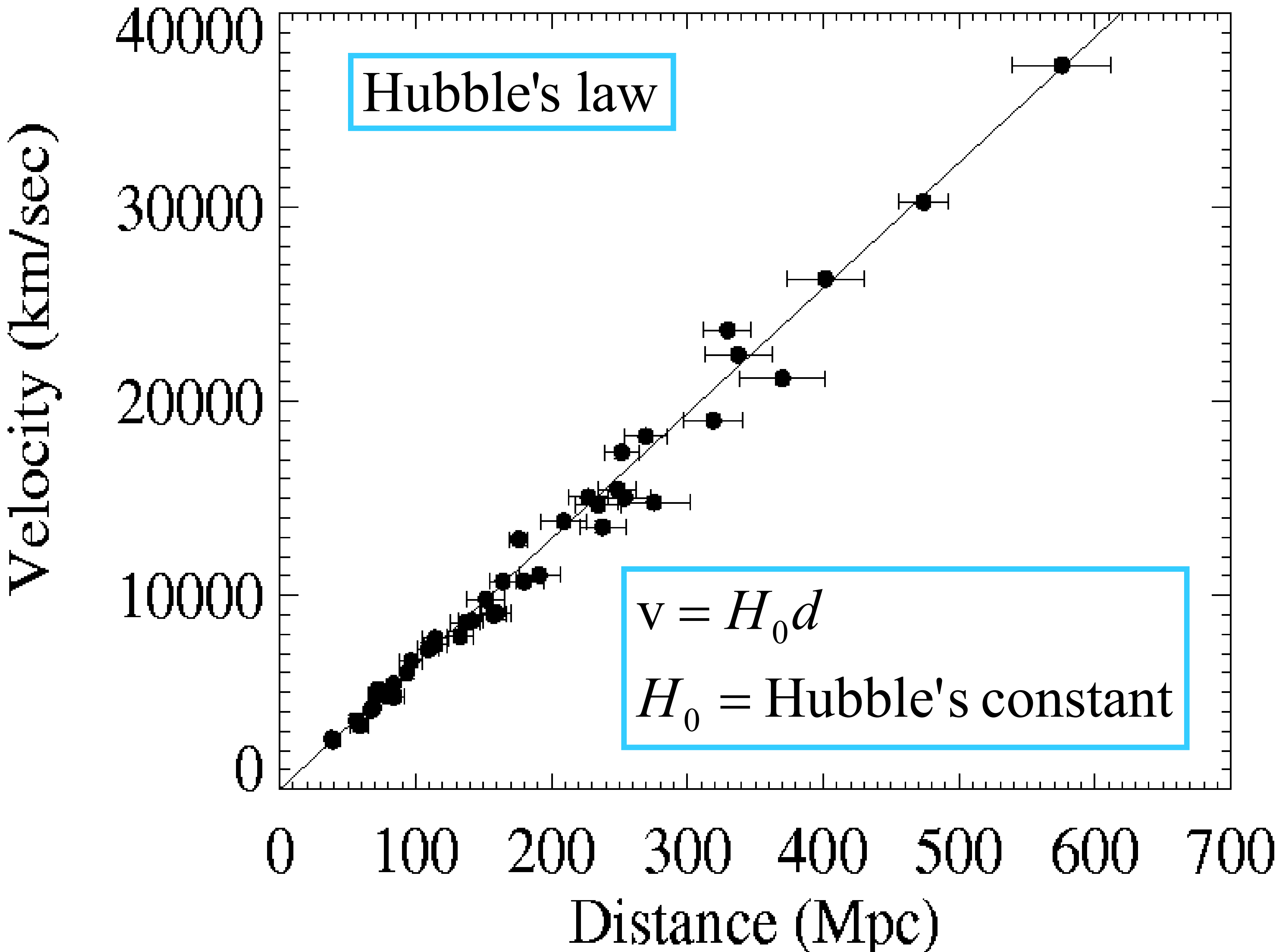
$- \rightarrow$ approaching (shorter λ)

$$\boxed{\begin{array}{l} \mathrm{v} = H_0 d \\ H_0 = \text{Hubble's constant} \end{array}}$$

Let's assume $H_0 = 100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

$$\mathrm{v} = 100\ \frac{\mathrm{km}}{\mathrm{s}} \frac{d}{\mathrm{Mpc}}$$

v	d
$100\ \mathrm{km\ s^{-1}}$	1 Mpc
$1{,}000\ \mathrm{km\ s^{-1}}$	10 Mpc
$10{,}000\ \mathrm{km\ s^{-1}}$	100 Mpc
$100{,}000\ \mathrm{km\ s^{-1}}$	1,000 Mpc



Hubble's law
$v = H_0 d$
H_0 = Hubble's constant
Velocity (km/sec)
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)